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NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

**FREEZING FOG FORMATION IN A SUPERCOOLED
BOUNDARY LAYER: SOLVING THE WINTER FOG
FORECASTING CHALLENGE FOR ELMENDORF AIR
FORCE BASE, ALASKA**

by

Bradley J. Harbaugh

March 2007

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**FREEZING FOG FORMATION IN A SUPERCOOLED BOUNDARY LAYER:
SOLVING THE WINTER FOG FORECASTING CHALLENGE FOR
ELMENDORF AIR FORCE BASE, ALASKA**

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN METEOROLOGY

from the

**NAVAL POSTGRADUATE SCHOOL
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ABSTRACT

We have examined four complex freezing fog events at Elmendorf Air Force Base, Alaska, to determine the root cause of the fog. These events have drastically impacted operations in the region for years, and are still a mystery to forecasters. The primary goal was to provide a detailed analysis of conditions within the boundary layer that contributed to freezing fog formation within the supercooled liquid water boundary layer. The data sets used to accomplish this goal were surface observations, upper air soundings, satellite images and water level data.

In the end, the fog was identified to be the result of moisture flux at the surface during high tide, which interacts with cold air from valleys northeast of the base. The interaction causes spontaneous condensation, and fog drains towards the base due to thermal gradients established from differential cooling from diurnal radiative properties.

A correlation exists between water levels and moisture flux, which is strong enough that forecasters should focus on water level data and wind speed and direction. Armed with this knowledge, the Air Force and the Department of Defense will reap the benefits of much more timely and accurate fog forecasts.

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TABLE OF CONTENTS

I.	INTRODUCTION.....	1
A.	MOTIVATION.....	1
B.	STATEMENT OF PROBLEM.....	2
C.	STUDY OBJECTIVE	2
II.	BACKGROUND.....	5
A.	THE “KNOWN”	5
1.	Types of Fog at Elmendorf AFB	5
2.	Horizontal Moisture Flux at the Surface	6
3.	Downslope Winds and Compressional Warming	6
B.	THE “UNKNOWN”	7
1.	Synoptic Scale Impacts.....	7
2.	Water Level Impacts	7
3.	Horizontal Moisture Flux above the Surface	7
4.	Gap Wind Cloud Formation	8
C.	GEOGRAPHY AND CLIMATE	10
1.	Geography.....	10
a.	<i>Elmendorf AFB</i>	11
b.	<i>Mountain Ranges</i>	12
c.	<i>Waterways</i>	12
2.	Climate.....	14
III.	DATA AND METHODOLOGY	17
A.	DATA	17
1.	Surface Observations.....	17
2.	Model Data.....	18
3.	Water Level Data.....	18
4.	Upper-Air Soundings.....	19
B.	METHODOLOGY	19
1.	Synoptic Overview.....	19
2.	Observational Analysis	19
3.	Water Level Impact	20
4.	Sounding Analysis	20
5.	Treatment of relative humidity measurements	21
IV.	RESULTS AND DISCUSSION	23
A.	OVERVIEW OF RESULTS	23
B.	CASE 1 (28-30 NOVEMBER 2005)	23
1.	Synoptic Overview.....	23
2.	Observational Analysis	26
3.	Sounding Analysis	31
4.	Case Summary.....	35
C.	CASE 2 (4 DECEMBER 2005).....	35

1.	Synoptic Overview.....	36
2.	Observational Analysis	39
3.	Sounding Analysis	45
4.	Case Summary.....	48
D.	CASE 3 (13-14 JAN 2006).....	48
1.	Synoptic Overview.....	49
2.	Observational Analysis	51
3.	Sounding Analysis	57
4.	Case Summary.....	62
E.	CASE 4 (18 JAN 06).....	63
1.	Synoptic Overview.....	63
2.	Observational Analysis	66
3.	Sounding Analysis	71
4.	Case Summary.....	74
F.	SUMMARY OF RESULTS	74
V.	SUMMARY AND CONCLUSIONS	79
A.	SUMMARY	79
B.	FORECASTING DRAINAGE FOG.....	81
C.	RECOMMENDATIONS FOR FUTURE RESEARCH	82
	LIST OF REFERENCES.....	85
	INITIAL DISTRIBUTION LIST	89

LIST OF FIGURES

Figure 1.	A surface analysis from 00Z on 11 Feb 1982 depicting the synoptic scale pattern conducive for Kamishak Gap Wind occurrence. From NRL Monterey, 1993.	8
Figure 2.	DMSP visible satellite imagery from 18Z on 15 Feb 1990, which shows a cloud line forming in Cook Inlet and stretching southward into the Gulf of Alaska as a result of the Kamishak Gap Winds. From NRL Monterey, 1993.	9
Figure 3.	Plan View Map showing the relationship between Anchorage (Elmendorf AFB) and the surrounding locations. From Geology and Science, 2006.	10
Figure 4.	A photograph of a mud flat in the Anchorage vicinity. From Virtual Tourist, 2007.	13
Figure 5.	Global air mass source regions. From NCEP, 2007.	14
Figure 6.	4-panel mean diurnal temperature curves (and 33 rd and 67 th percentil) for the months of November (top left), December (top right), January (bottom left) and February (bottom right) for Elmendorf AFB, AK. Temperatures along the y-axis in all charts are every 2°F, with the thick black line depicting the 0F line. From AFCCC, 1973.	15
Figure 7.	Sea-level pressure analysis for AK on 28 Nov 05 at 00Z. From NCEP/NCAR, 2007.	24
Figure 8.	Sea-level pressure analysis for AK on 29 Nov 05 at 00Z. From NCEP/NCAR, 2007.	25
Figure 9.	Sea-level pressure analysis for AK on 30 Nov 05 at 00Z. From NCEP/NCAR, 2007.	26
Figure 10.	Meteogram for PAED on 27 Nov 05. The meteograms have 5 blocks that depicts 12 different variables). Block 1. shows the temperature in Fahrenheit (TMPF), and the dew point temperature in Fahrenheit (DWPF). Block 2 shows the visibility in statute miles (VSBY) and the mean sea level pressure (PMSL). Block 3 shows the wind direction as a vector (DARR), the wind speed in knots (SKNT) and the wind gusts in knots (GUST). Block 4 shows the cloud cover at 3 levels (low, mid, upper) by type of cover (CLDS), the sky cover with wind barbs (SKYK), and the restriction to visibility (WSYM). Block 5 shows the surface potential temperature (STMA) and the surface equivalent potential temperature (STHE). From NCEP/NCAR, 2007.	27
Figure 11.	NOAA plot of water level vs. predicted water level for Anchorage, AK (Cook Inlet) for the period from 27 Nov-01 Dec 2005. From NOAA, 2007.	28
Figure 12.	Meteogram for PAED on 28 Nov 05. From NCEP/NCAR, 2007.	29
Figure 13.	Meteogram for PAED on 29 Nov 05. From NCEP/NCAR, 2007.	31

Figure 14.	RAOB data from 00Z on 28 Nov 2005. From UWSP, 2007.....	32
Figure 15.	RAOB data from 12Z on 28 Nov 2005. From UWSP, 2007.....	33
Figure 16.	Upper-air sounding from PANC launched at 00Z on 28 Nov 2005. From UWSP, 2007.	34
Figure 17.	Upper-air sounding from PANC launched at 12Z on 28 Nov 2005. From UWSP, 2007.	34
Figure 18.	Sea-level pressure analysis for AK on 03 Dec 05 at 06Z. From NCEP/NCAR, 2007.	37
Figure 19.	Sea-level pressure analysis for AK on 04 Dec 05 at 00Z. From NCEP/NCAR, 2007.	38
Figure 20.	Sea-level pressure analysis for AK on 05 Dec 05 at 00Z. From NCEP/NCAR, 2007.	39
Figure 21.	Meteogram for PAED on 03 Dec 05. From NCEP/NCAR, 2007.....	40
Figure 22.	Meteogram for PAED on 04 Dec 05. From NCEP/NCAR, 2007.....	42
Figure 23.	NOAA plot of water level vs. predicted water level for Anchorage, AK (Cook Inlet) for the period from 03 Dec-06 Dec 2005. From NOAA, 2007.	43
Figure 24.	Aqua-Modis 250m High Resolution visible image taken at 2135Z on 4 Dec 2005. From MODIS Rapid Response, 2007.....	43
Figure 25.	Meteogram for PAED on 05 Dec 05. From NCEP/NCAR, 2007.....	44
Figure 26.	RAOB data from 00Z on 04 Dec 2005. From UWSP, 2007.....	45
Figure 27.	RAOB data from 00Z on 04 Dec 2005. From UWSP, 2007.....	46
Figure 28.	Upper-air sounding from PANC launched at 00Z (top) and 12Z (bottom) on 4 Dec 2005. From UWSP, 2007.....	47
Figure 29.	Sea-level pressure analyses for AK on 13 2006 at 00Z. From Plymouth State Weather Center, 2007	50
Figure 30.	Sea-level pressure analyses for AK on 14 Jan 2006 at 00Z. From Plymouth State Weather Center, 2007	50
Figure 31.	Sea-level pressure analyses for AK on 15 Jan 2006 at 00Z. From NCAR/NCEP, 2007	51
Figure 32.	Meteogram for PAED on 12 Jan 06. From NCEP/NCAR, 2007.	52
Figure 33.	NOAA plot of water level vs. predicted water level for Anchorage, AK (Cook Inlet) for the period from 12-14 Jan 2006. From NOAA, 2007.	53
Figure 34.	Meteogram for PAED on 13 Jan 06. From NCEP/NCAR, 2007.	54
Figure 35.	Aqua-Modis 250m High Resolution visible images taken on 13 Jan 2006. From MODIS Rapid Response, 2007.....	55
Figure 36.	Meteogram for PAED on 14 Jan 06. From NCEP/NCAR, 2007.	56
Figure 37.	Aqua-Modis 250m High Resolution visible images taken on 14 Jan 2006. From MODIS Rapid Response, 2007.....	57
Figure 38.	Upper-air sounding from PANC launched at 00Z 13 Jan 2006. From UWSP, 2007.	58
Figure 39.	Upper-air sounding from PANC launched at 12Z 13 Jan 2006. From UWSP, 2007.	59

Figure 40.	Upper-air sounding from PANC launched at 00Z 14 Jan 2006. From UWSP, 2007.....	60
Figure 41.	Upper-air sounding from PANC launched at 12Z 14 Jan 2006. From UWSP, 2007.....	61
Figure 42.	Upper-air sounding from PANC launched at 00Z 15 Jan 2006. From UWSP, 2007.....	62
Figure 43.	Sea-level pressure analyses for AK on 17 Jan 2006 at 00Z. From NCAR/NCEP, 2007	64
Figure 44.	Sea-level pressure analyses for AK at 00Z on 18 Jan (top) and 00Z on 19 Jan (bottom) 2006. From NCAR/NCEP, 2007	65
Figure 45.	Meteogram for PAED on 17 Jan 06. From NCEP/NCAR, 2007.	67
Figure 46.	NOAA plot of water level vs. predicted water level for Anchorage, AK (Cook Inlet) for the period from 17-20 Jan 2006. From NOAA, 2007.	68
Figure 47.	Meteogram for PAED on 18 Jan 06. From NCEP/NCAR, 2007.	69
Figure 48.	Aqua-Modis 250m High Resolution visible images taken on 18 Jan 2006. From MODIS Rapid Response, 2007.....	70
Figure 49.	Meteogram for PAED on 19 Jan 06. From NCEP/NCAR, 2007.	70
Figure 50.	Upper-air sounding from PANC launched at 12Z 17 Jan 2006. From UWSP, 2007.....	71
Figure 51.	Upper-air sounding from PANC launched at 00Z 18 Jan 2006. From UWSP, 2007.....	72
Figure 52.	Upper-air sounding from PANC launched at 12Z 18 Jan 2006. From UWSP, 2007.....	73
Figure 53.	4-pan sea-level pressure analyses for AK at 00Z on 28 Nov 05(top left), 04 Dec 05(top right), 13 Jan 06 (bottom left) and 18 Jan 06 (bottom right). From NCAR/NCEP, 2007	75
Figure 54.	3-D Depiction of Drainage Fog Formation. The moisture source to the north drifts south. Map courtesy of Google Earth, 2007.	80
Figure 55.	Drainage Fog Forecasting Flow Chart. This should be utilized by forecasters anytime the forecasted low temperature is expected to be below -3°C.....	82

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I. INTRODUCTION

A. MOTIVATION

Since its establishment on 27 June 1940, Elmendorf Air Force Base (AFB), Alaska (AK), has proven to be one of the most critical bases in defense of the United States from foreign enemies to the west. The strategic location of Elmendorf AFB has made it an excellent deployment center, a fact that validates the contention of Billy Mitchell, who, in 1935, stated that "Alaska is the most strategic place in the world." (www.elmendorf.af.mil). Aircraft such as the F-80, F-94 and F-102 were some of the original aircraft to take to the skies over South-Central Alaska. Then, during the early 1990's, the F-15E arrived (with the transfer of the 3rd wing from Clark AB in the Philippines), making Elmendorf AFB a lethal base; one that could accomplish multi-role missions with an unlimited range. Today, Elmendorf AFB awaits the arrival of a squadron of F-22 Raptors, the Air Force's latest and most advanced aircraft. And because of this, there is a yearning desire to have consistent and accurate weather forecasts in order to ensure the safety of both personnel and of the Air Force's most elite aircraft.

One of the greatest forecast challenges that weather predictors face at Elmendorf AFB is freezing fog during the winter months. The fog forms mainly during the overnight hours, and typically forms in a supercooled sub-saturated water boundary layer that saturates seemingly spontaneously. This is a grave challenge for forecasters, because with the rapid development of fog, aircraft and operators can either get cancelled from a mission that time and money has been spent on already, or even worse, can get trapped away from base by the fog, and may not be able to safely land. Therefore, it is important to try to further identify the specific causes for winter fog formation in order to enable the key decision-makers the ability to ensure flight and personnel safety, and to ensure mission success!

B. STATEMENT OF PROBLEM

Before this study, there have been few attempts to uncover the mystery of winter fog formation at Elmendorf AFB. The Air Force Combat Climatology Center (AFCCC) in 1973 did an extensive fog study as part of a Technical Forecasting Reference Notebook (TFRN) that describes not only probable causes, but techniques for forecasting winter fog events. This study, however, pointed towards the more commonly known fog types in the region, such as radiation and advection fog.

This thesis, unlike the studies before it, set out to unravel the mystery specifically associated with freezing fog within the supercooled boundary layer. This was accomplished by first performing a review of previous studies to determine applicable information that could be useful to this study. Then, a case review of four events was accomplished in order to find similarities within the cases. Once correlations were made, the common parameters were highlighted to assist forecasters for Elmendorf AFB. Finally, a list of possible parameters for which either sufficient data or evidence was unavailable, or that sufficient subject matter knowledge was not available, were recommended for future research.

C. STUDY OBJECTIVE

The overall goal of this study is to understand the perplexity of freezing fog formation and the critical parameters to forecast the fog.

In order to get enough information to understand the complexity of the freezing fog formation, four cases were researched and studied. These cases were chosen for three main reasons: 1) All of these events were unforecasted fog events, 2) Each case had visibilities that were reduced well below flight minimums for a significant period of time, 3) There was little to no precipitation occurring during the events, since this is known to reduce visibilities. At the end

of the study, the results were compiled, and correlations were made if they could be. This in turn should enable forecasters to better understand and forecast freezing fog formation.

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II. BACKGROUND

To begin to understand the fog forecasting challenge during the winter months at Elmendorf AFB, it was important to review the meteorological “knowns” and “unknowns” that pertain to these events. The next few sections give a general description of assumptions that were applicable to this study and highlight some of the areas that are not well-understood as they may apply to the cases within.

A. THE “KNOWNs”

1. Types of Fog at Elmendorf AFB

Up until now, most studies for this region focused on four different types of common fog events: Radiation Fog, Steam Fog, Dynamically Forced Fog, and Lowering Stratus. Radiation fog develops as a result of rapid cooling at the surface from outgoing terrestrial radiation at night. Winds are typically light, and surface moisture is readily available during radiational fog events. Steam fog is similar to radiational fog, in that winds are typically light and the surface is cool, although it is usually cool as a result of air mass conditions and not due to radiational characteristics. Steam fog, however, has a moisture source from the ground, that provides ample moisture flux into the boundary layer that saturates upon contact with the ambient air. Dynamically forced fog occurs when the boundary layer structure changes, and in this region, is the result of strong subsidence capping off the top of the boundary layer, enabling the low-levels to gain saturation from the snow cover at the surface over a period of days. Finally, lowering stratus, which is similar to the dynamically forced fog, is the result of a stratus deck being lowered through cooling at the top of the cloud deck as a result of evaporational and longwave outgoing radiational cooling. This occurs typically under strong subsidence, and clear skies above the stratus, allowing maximum cooling at the top of the cloud. The fog occurrences at Elmendorf AFB

during this study may not be categorized by any one of these categories, but are rather a combination of all of the fog types put together.

2. Horizontal Moisture Flux at the Surface

Critical to the formation of any fog is a source of moisture to effectively moisten the low-level atmosphere, and allow condensation to occur. A previous study in this region identified numerous source regions for moisture. AFCCC in 1973 cited the cooling ponds just south of runway 35 as excellent sources of moisture (and heat) during the winter months, as they tend to stay around 1-6°C. Cook Inlet was also identified to be a moisture source, although, the extent of ice coverage and tidal variations were never presented, nor was Cook Inlet or either of its arms ever directly linked to fog formation over the base.

3. Downslope Winds and Compressional Warming

The study by AFCCC in 1973 highlighted the fact that Eagle River Flats (approximately 200 feet (ft) high and at a heading of 020 from the base at a distance of 1.5 miles) were excellent source regions for drainage flow to the base. The study, therefore, cited winds from the north as being favorable for fog formation, since the drainage flow was expected to be cold, and would assist the near surface layer in cooling to saturation. The study also cited the Chugach Mountain Range east of the base as a source of Chinook Winds. But, the study also determined that Chinook Winds would not be favorable for fog, and in fact would be unfavorable, since the addition of warm (and presumably dry) air near the surface would help to destabilize the boundary layer and would demote condensation. While this statement is true, some destabilization of the boundary layer near the surface promotes weak turbulent mixing in the vertical and helps lower the stratus deck when the moist boundary layer air is not completely mixed.

B. THE “UNKNOWNNS”

1. Synoptic Scale Impacts

Fog formation in this region has long been considered a microscale feature, since it often forms in a narrow region between Cook Inlet and the Chugach Mountains. It is believed, however, that the synoptic scale pattern plays a large role in the formation of freezing fog, because of the fact that there is a certain air mass that is required to be in place. Freezing fog only appears to form when the temperature at the surface is very cold, which leads to the conclusion that a cP or cA air mass is favorable to the formation. In order for a cold air mass to be in place, the synoptic scale pattern needs to be oriented in such a way to allow winds to advect cold air towards the base.

2. Water Level Impacts

The Anchorage Peninsula is known to have the 2nd largest tidal variation in the world, ranging +/- 30 ft. This strong moisture surge is known to fill mud flats with water along Cook Inlet and Knik and Turnagain Arms. While the impact of tidal variation on fog formation has been proposed in other regions, such as S. Korea and Savannah, GA, Anchorage is unique in that the entire area is snow and ice covered during the winter months, to include some of the waterways. The impact of tide cycles on fog formation has never been accomplished, but will be reviewed in this study.

3. Horizontal Moisture Flux above the Surface

No previous study in the region had discussed the moisture advection above the surface and instead focused only at the surface. While surface moisture flux is normally considered important to fog formation through advective process, the Elmendorf AFB region is slightly different, since it sits down below surrounding elevation. This means that air from higher elevations that sinks into the region would be advecting moisture above the surface, rather than at the

surface. If this is true, than the possibility of freezing fog formation being dependent on moisture flux just above the surface is possible. This study will try to determine the impact of moisture flux just above the surface.

4. Gap Wind Cloud Formation

A previous study showed the effects of the Kamishak Gap wind over Cook Inlet, and that cloud bands formed and extended for hundreds of miles, as the result of cold air flowing rapidly over warmer areas of open water.

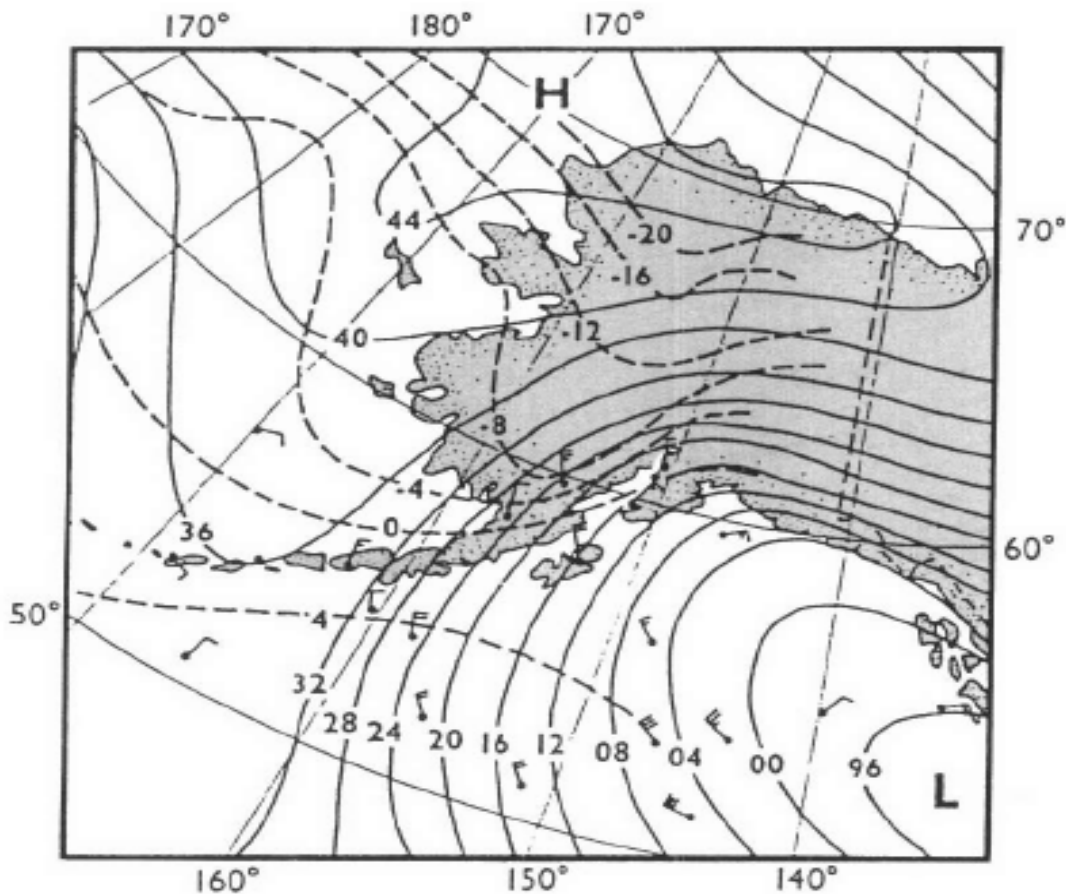


Figure 1. A surface analysis from 00Z on 11 Feb 1982 depicting the synoptic scale pattern conducive for Kamishak Gap Wind occurrence. From NRL Monterey, 1993.

The synoptic pattern that is favorable for Kamishak Gap Winds (Fig. 1) includes a low in the Gulf of Alaska interacting with a ridge to the north (in central Alaska). This pressure pattern is conducive for winds from the north at the surface, and the northeast just above the surface. These cold winds channel through the Kamishak Gap and out over the warm, moist Cook Inlet, where stratocumulus forms. This event, although well south of Elmendorf AFB, is indicative of what is possible in the vicinity of the base when winds come from the north and interact with the warm, moist mudflats and leads that occur during high tide.

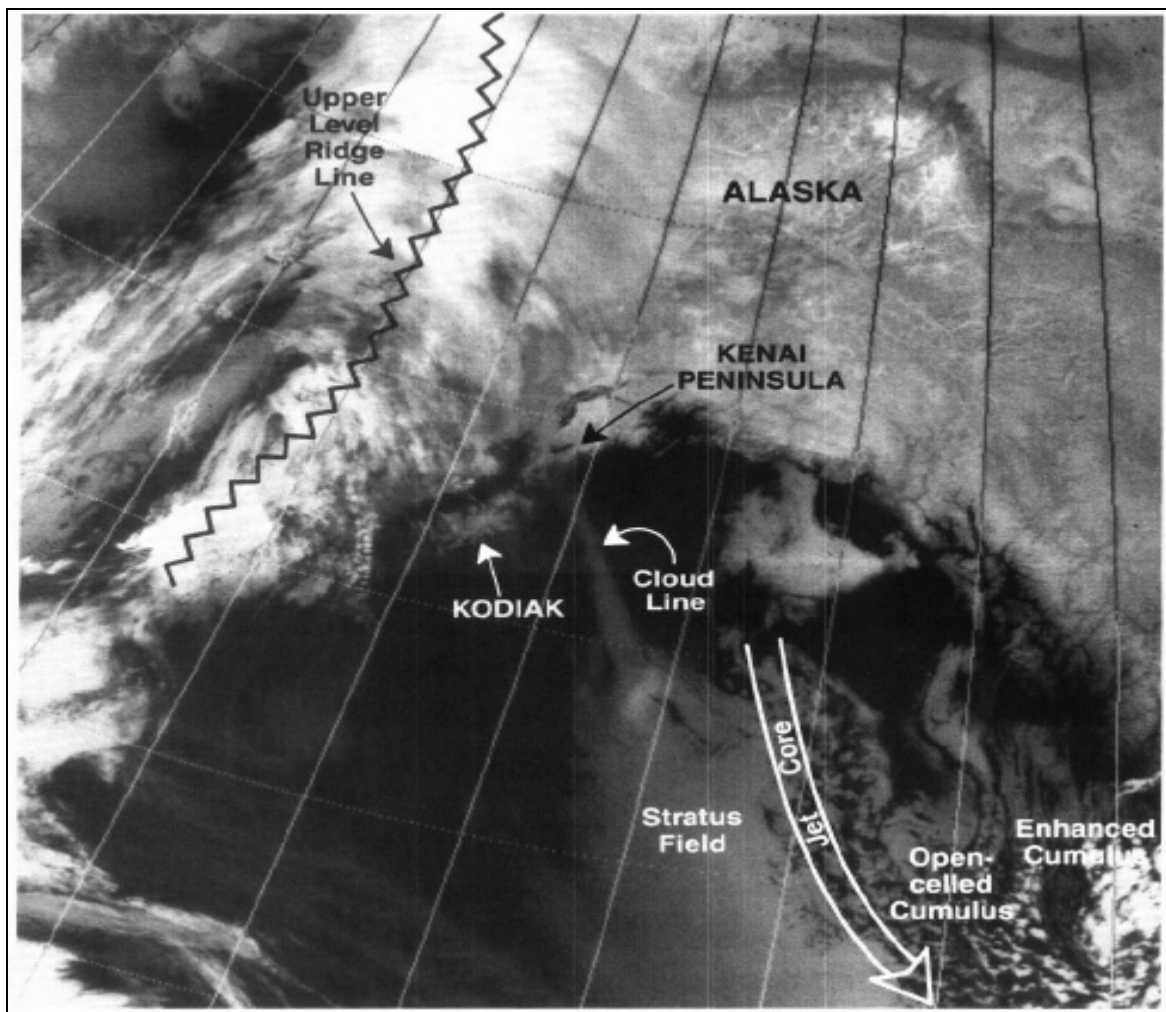


Figure 2. DMSP visible satellite imagery from 18Z on 15 Feb 1990, which shows a cloud line forming in Cook Inlet and stretching southward into the Gulf of Alaska as a result of the Kamishak Gap Winds. From NRL Monterey, 1993.

C. GEOGRAPHY AND CLIMATE

1. Geography

The focus of this study will be the geographical “box” that spans from 59°N, 153°W to 63°N, 147°W, with a detailed look at Elmendorf AFB which is at 61.15°N, 149.48°W (AFCCC, 06). Portions of the Gulf of Alaska will also be noted, since each event involved a synoptic low pressure system in the Gulf.

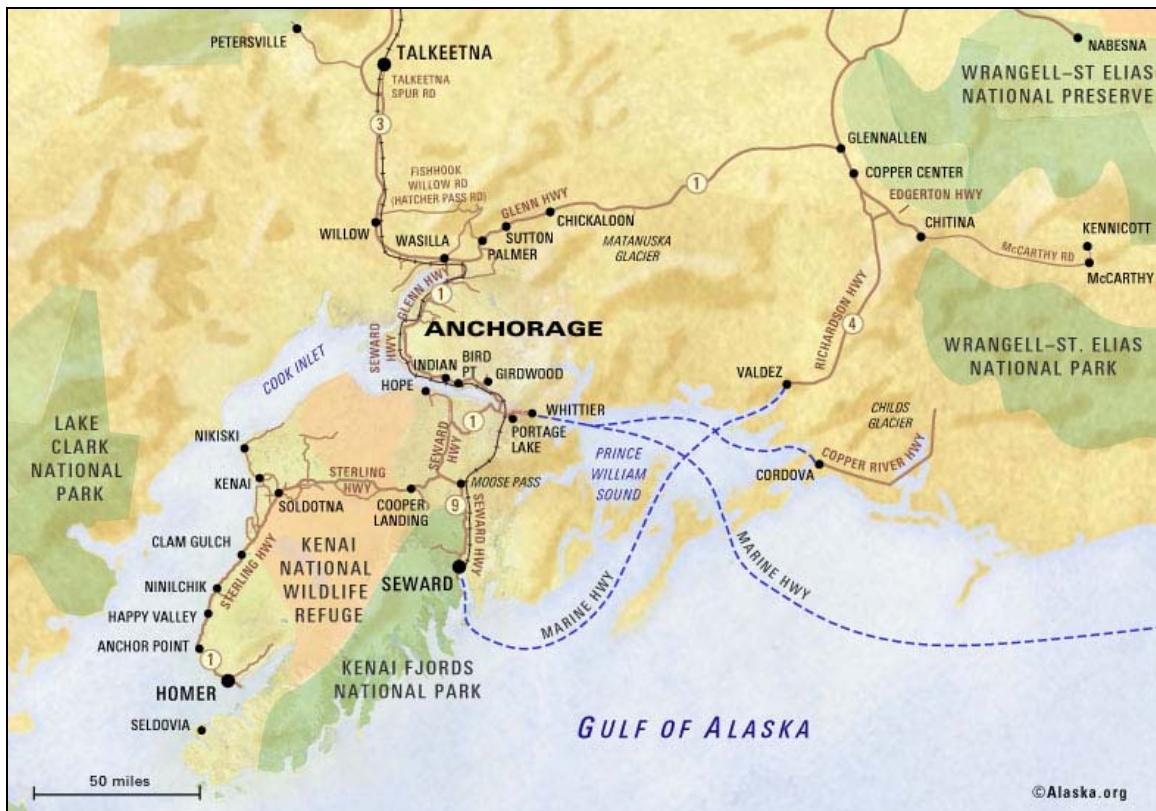


Figure 3. Plan View Map showing the relationship between Anchorage (Elmendorf AFB) and the surrounding locations. From Geology and Science, 2006.

The complex terrain in and around Elmendorf AFB was undoubtedly responsible for much of the forecasting challenge experienced in the region. There were not many observations present in the immediate vicinity, and many of the observations that were within the necessary scale length (~10 Statute Miles (SM) or less) were at much different elevations than the base. The mountains to

the east serve as a barrier for low-level air flow, and thus, the base weather was often somewhat different in terms of air mass regime than were the surrounding areas. To the west, Cook Inlet serves as a major moisture source. The inlet is mountain-lined on the west side, which forces the wind into a “gap-like” flow as it stretches northward (Fitton, 1930). The plan view of The Anchorage and Kenai Peninsula in Fig. 3 shows some of the geographical features in and around the area. To add yet another wrinkle to the forecast challenge, much of the land is snow covered and the inlet is partially ice covered during the winter months (Kyle and Brabets, 2001).

a. *Elmendorf AFB*

Elmendorf AFB is located at 61.15°N, 149.48°W at 212 ft above sea-level, in the south-central part of Alaska, and takes up approximately 13,130 acres of land (<http://ludb.clui.org>). The base is located 7.3 miles from Anchorage, the largest city in Alaska. Surrounding the base are three major mountain ranges; the Chugach to the east, the Alaskan to the northeast, north and northwest, and the Aleutian to the west (AFCCC, 1973). Locally, however, there are smaller peaks on portions of the base. Approximately one mile north of the base (with a northeast to southwest orientation) is a 300 ft high ridge which has a width of 0.5 miles. This ridge descends sharply to the tidal mudflats. Because of the sharp descent and the closeness to the base, this ridge is a considerable source for cold drainage flow (AFCCC, 1973).

The base has two major runways; 06/24 which is 10000 ft long and 200 ft wide, and 16/34 which is 7505 ft long and 150 ft wide (www.globalair.com). In the immediate vicinity of the base are a wide variety of streams, small lakes and tundra, with large trees along some streams in the valley. The largest stream in the region is Ship Creek, which passes approximately 1000 ft from the south end of runway 16/34. Ship Creek is also home to some large cooling ponds used for the base’s heating plants. These ponds range in temperature

from 1-6°C during the year, and since they never freeze, serve as excellent fog moisture sources during the winter months (AFCCC, 1973).

Pollutants were not considered to be a major factor, since most of the surrounding region is uninhabited and pure (AFCCC, 1973). This precluded pollutants from being considered a potential source for cloud condensation nuclei (CCN). Sea salts were also not going to be considered significant for this study, since the major source of sea salt is well south (Gulf of Alaska). Most of the water ways in close proximity to the base are fresh water or minimally brackish, and therefore, do not provide a substantial source of CCN.

b. Mountain Ranges

There are three mountain ranges that play an important role in the surface weather conditions at Elmendorf, and these are the Chugach Range, Alaskan Range and Aleutian Range. The Chugach range is perhaps the most critical to weather at Elmendorf, because of its proximity to the east. When winds shift to an easterly direction, weak Chinook winds can develop, which is believed to be destructive to fog formation, since it should deepen the mixed layer. This study, however, revealed that if winds were light enough, the warm air could actually promote fog through weak vertical mixing of stratus to the surface. The importance of the Chugach Range will be highlighted during the case reviews.

c. Waterways

Cook Inlet is approximately 195 miles long, and separates the Alaskan Mainland from Kenai Peninsula. As it makes its way north from the Gulf of Alaska, it splits into two arms; Turnagain Arm and Knik Arm. The inlet and arms have an average winter temperature of 31°F (with a range of +/- 1°F), but due to tidal variations, the inlet rarely freezes solid. Turnagain Arm is the more southern of the two arms, and makes a hard turn to the east, heading just south of Anchorage and Elmendorf AFB, while Knik Arm makes a more subtle turn to the northeast, heading west and then north of Anchorage and the base. Knik

Arm comes much closer to Elmendorf AFB, with the nearest point being only 4 miles at a direction of 285 degrees. Turnagain Arm is somewhat further away, coming as close as 12 miles at a heading of 200 degrees from the base. These two arms are enough to provide a significant source of moisture into the boundary layer during the summer months.



Figure 4. A photograph of a mud flat in the Anchorage vicinity. From Virtual Tourist, 2007

During the winter, some surface ice cover is typical on top of both arms, since they have an approximate depth between 60-80 feet, and currents are reduced to near 1 meter per second (m/s) (Li et al., 2004). And, to complicate matters, a mean diurnal tide range of 30.0 ft is observed in both arms (tidesandcurrents.noaa.gov). This tidal variation leads to an area known as the “mudflats”, which are broad areas of land along the banks of the Cook Inlet that fill with water during high tide, and then drain and partially freeze during low tide if temperatures are cold enough. These mudflats are known to be a significant moisture source during the winter months, and during this study, it was determined that the tides do in fact play a role in the formation of stratus.

Ultimately, the moisture was advected over the base, and appeared to be mixed to the surface in some of the events. While the exact correlation could not be determined from four cases, it was evident that there is likely a correlation, and that future studies should dig deeper into this area.

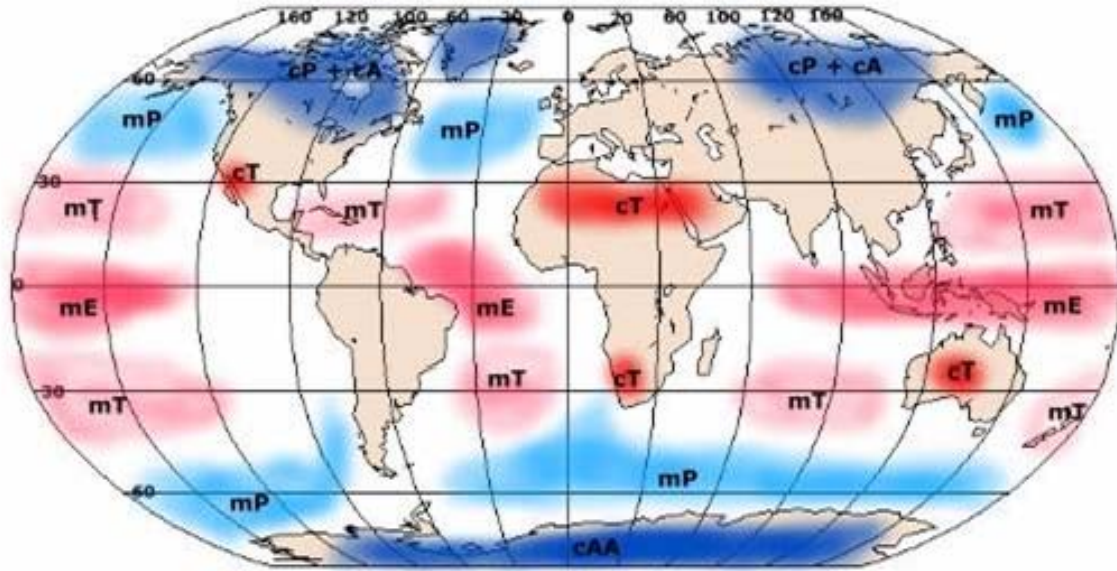


Figure 5. Global air mass source regions. From NCEP, 2007.

2. Climate

There are three major types of air masses that affect Elmendorf AFB during the winter: Continental Arctic (cA), Continental Polar (cP) and Maritime Polar (mP) (Fig. 5). One thing of particular interest was the numerous source regions that have a close proximity to Elmendorf AFB. This is troublesome to local forecasters for a couple of reasons. First, it is often hard to determine whether or not an air mass change will occur as expected because of the natural geographical mountain barriers. Air masses are often blocked from entering the Anchorage Peninsula, or are trapped by these mountains. The other challenge is to know which air mass is going to dominate when two air masses interact. It was common during this study to see a cold and dry cA air mass move in from

the northwest associated with a Siberian High, while a much warmer and moister mP air mass would move in from the southeast from a low pressure center in the Gulf of Alaska. The surface conditions were often characterized by the cP air mass, since it was colder and was able to undercut the warmer and moister mP air mass. These were just two of the many challenges that forecasters face during the winter months as a result of air mass interaction.

The mean diurnal temperature range for 4 winter months can be seen in Fig 6. These graphs show that the daily temperature range is less than 5°C during the winter and only 1-2°C during the months of December and January. This small range certainly limits the diurnal variation of fog structure and evolution, to prevent “burn-off” of an established fog layer.

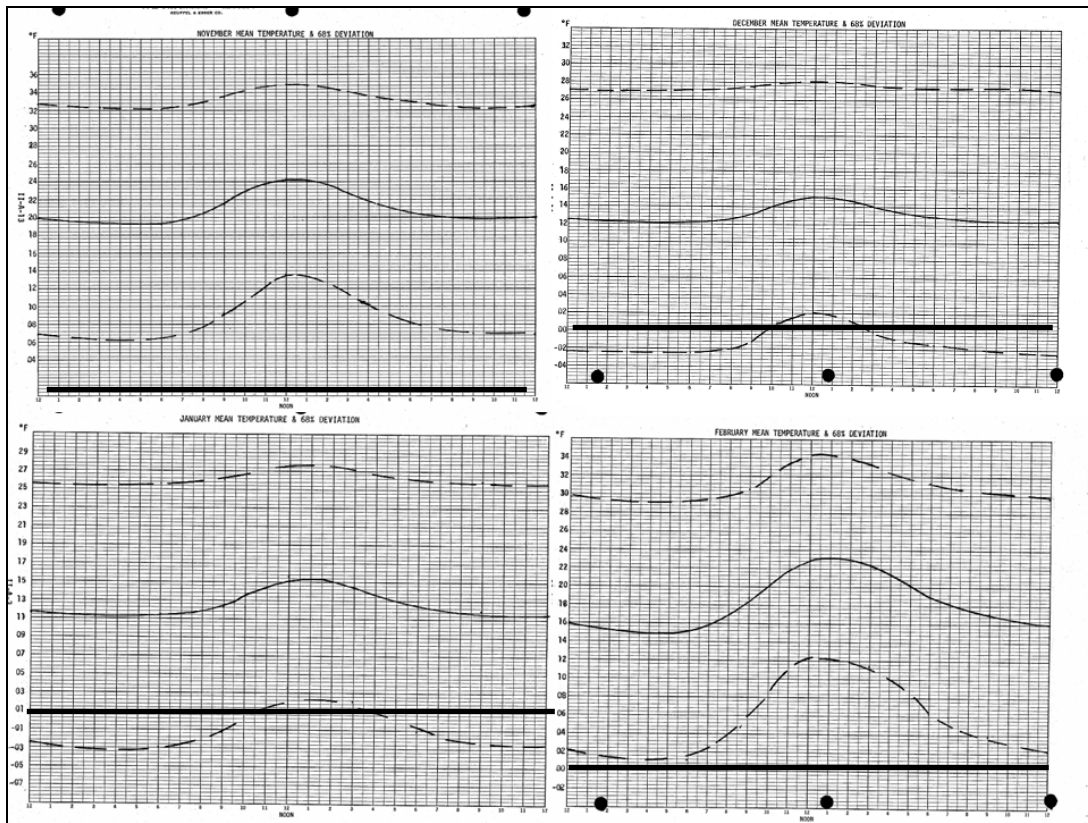


Figure 6. 4-panel mean diurnal temperature curves (and 33rd and 67th percentil) for the months of November (top left), December (top right), January (bottom left) and February (bottom right) for Elmendorf AFB, AK. Temperatures along the y-axis in all charts are every 2°F, with the thick black line depicting the 0°F line. From AFCCC, 1973.

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III. DATA AND METHODOLOGY

A. DATA

The data for this research was gathered from numerous locations and institutions in order to try and capture the best picture of the synoptic, mesoscale, and microscale features. One thing that became obvious in attempting to gather data is that Alaska in general is very data sparse. The Anchorage Peninsula, however, was fairly dense with surface observations, which helped to provide a bit more detailed surface flow picture than was anticipated. Unfortunately, the other atmospheric data, such as upper-air soundings and satellite imagery, was very limited.

1. Surface Observations

Somewhat surprising was the relatively dense amount of surface observations available in the southern portion of Alaska. While the number of METAR reporting stations is fairly limited (~16 in the 43,000+ square mile “geographical box” looked at in this study), nearly 30 mesonet stations in the region reported at least one of the following parameters: wind direction and speed, temperature, dew point temperature, dew point depression, or relative humidity. These additional 30 stations are observation sites maintained by various agencies and were downloaded from Meteorological Assimilation Data Ingest System (MADIS). The surface observations were the most useful and abundant tool in this research, since observations were available hourly and sometimes more often based on special criteria.

Observations for each case were collected 12 hours prior to the time of the first occurrence of prolonged fog, and ending 12 hours after the last observation. This provided data for the pre-fog conditions, and also for the dissipation and post-fog conditions. The primary observations used were from Elmendorf AFB (PAED), since this study is specific to fog at the base. However,

since Anchorage International Airport (PANC) is only 6 miles away, and was the next nearest full-time METAR site, these observations were also scrutinized in high detail. The other observations in the area were examined to determine upstream/downstream trends, as well as to try to determine the movement of the boundary layer in the “bowl” within which Elmendorf AFB lies.

2. Model Data

The model data used for this research came from the National Center for Environmental Prediction (NCEP) Global Tropospheric Analysis dataset. The Global Final (FNL) Analysis contains records of global atmospheric fields at a 1° latitude x 1° longitude resolution from 1999-present at 6-hour intervals. The analyses are available on the surface, 26 mandatory (and other pressure) levels from 1000mb to 10mb, boundary and some sigma layers, tropopause and a few others. Parameters include surface pressure, sea level pressure, geopotential height, temperature, sea surface temperature, soil values, ice cover, relative humidity, u- and v- winds, vertical motion, vorticity and ozone.

The data sets for this study included the dates from 27 Nov 2005 to 31 Jan 2006. While the model sets used in this study were relatively useless to define boundary layer details important to the microscale meteorological physics of fog, they did provide a consistent synoptic scale overview.

3. Water Level Data

Water level data was compiled from the National Oceanic and Atmospheric Association (NOAA), and was used to help determine the possible correlation between the appearance of moisture within the boundary layer, and the level of water in Cook Inlet and its arms. The data was gathered for the same times that observations were collected.

4. Upper-Air Soundings

Upper-air soundings for the first two cases were taken every 12-hours at 00Z and 12Z local (15L and 03L respectively), with the closest coming from PANC. The second two cases had some staggered off-hour soundings at 06Z and 18Z at PANC, in addition to the routine 00Z and 12Z. This data was available from numerous sources (Naval Postgraduate School (NPS), Plymouth State, University of Wisconsin at Stevens Park (USWP), and NCEP). The RAOB data was used to understand the general changes that occurred on a diurnal basis, such as rising or lowering of the inversion, drying or moistening of low-mid levels, and wind changes at all levels. This tool provided the most useful information to characterize the subtle changes that were occurring.

B. METHODOLOGY

To determine the key physical processes and events common to the fog formation in these cases, the synoptic structure, detailed mesoscale features, and microscale parameters were examined using all available data.

1. Synoptic Overview

Thy synoptic scale patterns and motions in each case were reviewed, to include standard plots at 850mb, 925mb, 975mb and 1000mb, which were examined in detail for wind, temperature and moisture characteristics. This information was used to help better understand the air mass characteristics present during the fog events.

2. Observational Analysis

At the surface, temperature, dew point temperature, wind velocity, ceilings and visibilities were used from Elmendorf AFB to describe the observed boundary layer. A time series of station plots was developed before and during the events to highlight changes on station from observation-to-observation. Other observations from the area were used to gain general information into the

characteristics of the air mass surrounding the base, and to determined possible small-scale movements of fog and clouds within the region.

3. Water Level Impact

The potential impact of water level on boundary layer moisture in this region is believed to be great. Therefore, a detailed review of the timing of high and low tide was compared to the timing of the development of stratus (based on observations at PAED and PANC), and the onset of fog. Since an increase in the water level inevitably increased the surface moisture area through both the opening of leads and the filling of mud flats, and observation of moisture (stratus) or fog that occurred within 4 hours of high tide was believed to be correlated. Since winds in all of the events were on the order of 5 kts or less, this 4 hour window was created to help allow for the time it would take the stratus or fog to advect to the base from the moisture source near Knik Arm.

4. Sounding Analysis

Upper-air profiles courtesy of rawindesondes were used for three purposes. First, the data helped to verify the synoptic scale air mass changes occurring within the region. Wind speeds and directions above 850mb were reviewed to determine the location of speed maxes over PANC, which provided details into the possible vertical motions within the column of air. Second, the data was useful in determining the height and movement of the boundary layer, as well as the strength of the inversion. Moisture and temperature changes were more easily visible using RAOB data than they were through model data. Finally, characteristics about the entrainment of dry air into the top of the boundary layer were easily seen with RAOB data. Having this information provided the ability to determine whether the fog was undergoing strengthening or weakening due to conditions near the top of the boundary layer.

Within the boundary layer, three levels were broken down for detailed analysis: Surface-975mb, 975-925mb and 925-850mb. The first layer was

selected because the fog layer during this research was never thicker than 300m, so this layer best represented the saturated portion of the boundary layer. The second level from 975mb-925mb was selected because there was often dry air in place at this level, which was believed to have an impact on the duration of the fog events. Finally, the level from 925mb-850mb was selected, because it is the level at or near the top of the inversion, but not at a height above the local mountain-tops. Therefore, the interface at this level helped to describe what physical and dynamical processes were taking place such as evaporational cooling, dry air entrainment and cloud-top radiational cooling. The combined scrutiny of these three levels was done to provide a detailed explanation of what meteorological parameters drove the formation of the fog.

5. Treatment of Relative Humidity Measurements

In reviewing observations, the temperature almost never reached the dew point temperature, yet saturation obviously had occurred. This led to research into the calculation required to determine relative humidity values within a supercooled-liquid water boundary layer.

A previous study found that “the relative humidity (in polar regions) is frequently well above the frost point, both due to radiative cooling and to the advection of moist air, and that the conventional humidity measurements were unable to detect these events.” (Makkonen and Lakso, 2005). This was the case as well for the fog events in this research. Therefore, a reasonable conclusion was made that a 3°C or less measured dew point depression was satisfactorily representative of a fully saturated boundary layer in the event of freezing fog. While it is uncertain to what extreme the sensor discrepancy occurs without further studies of the sensor, or what impact the supercooled liquid water itself may have on relative humidity measurements, it is certain that fog was observed with a dew point depression as high as 3°C.

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IV. RESULTS AND DISCUSSION

A. OVERVIEW OF RESULTS

This section will discuss the results of analysis of the four fog events selected for research. Each case was examined in detail looking at the synoptic pattern, the observations, the water level data, and the upper air data. The key focus was to accurately determine the processes that caused the fog formation and evolution.

B. CASE 1 (28-30 NOVEMBER 2005)

The first case is perhaps the most dramatic of the events that was analyzed in this study. The sequence of events leading up to the fog started with a pressure gradient strengthening over the base as a result of a high to the northeast of the base and a low to the southeast of the base interacting. The winds just above the surface were from the north, and brought cold air in from the Alaskan Plateau. A stratus deck formed and moved over The Anchorage Peninsula late in the day on 27 Nov, just 2 hours after high tide, and only 3 hours before the first report of freezing fog, which reduced visibilities to 1/16 SM. The fog continued to remain thick through most of the day, with only a few periods of time when the visibility was up above 1SM. Freezing fog remained in place through 30 Nov, when snow began to fall. This marked the end of the long stint of freezing fog at Elmendorf AFB.

1. Synoptic Overview

As is typical in the wintertime, Elmendorf AFB was in a transition regime between a Siberian High and a Gulf of Alaska Low at the start of the fog event. The low pressure center was nearly 400NM southeast of the base with an inverted trough stretching northwestward towards the region. This trough interacted with a ridge settled over the Alaskan Interior and a strong trough off

the west coast of Alaska (Fig. 7). The resultant pressure gradient led to northerly wind flow at the surface, and allowed cold air to drain over the mountains from the north. This caused a cold outbreak to impact the region, with temperatures at the surface some 10°C below normal, based on the November monthly mean.

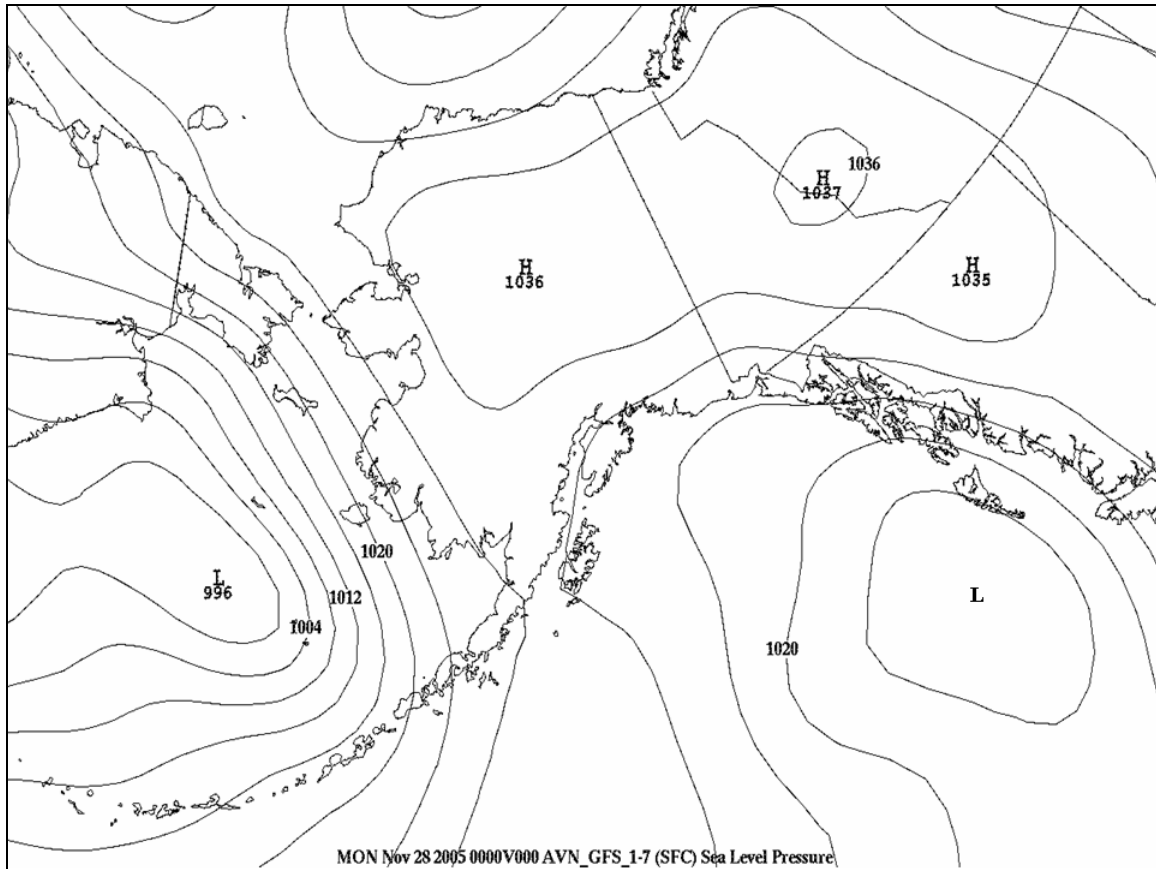


Figure 7. Sea-level pressure analysis for AK on 28 Nov 05 at 00Z. From NCEP/NCAR, 2007.

On the following day, the Gulf of Alaska Low had strengthened, and the associated trough began to closely follow the contours of the Alaskan coastline. The ridge to the north of the base had begun to sag towards the base (Fig. 8), which was also noted in upper air profiles where pressures were on the rise. The pressure gradient along the west coast of Alaska weakened slightly, and helped to relax the winds aloft over the base, which in turn appeared to prohibit vertical mixing in the lower portion of the atmosphere. The winds at the surface had a

northeasterly component, though, and were presumably being shielded by the mountains to the east of the base.

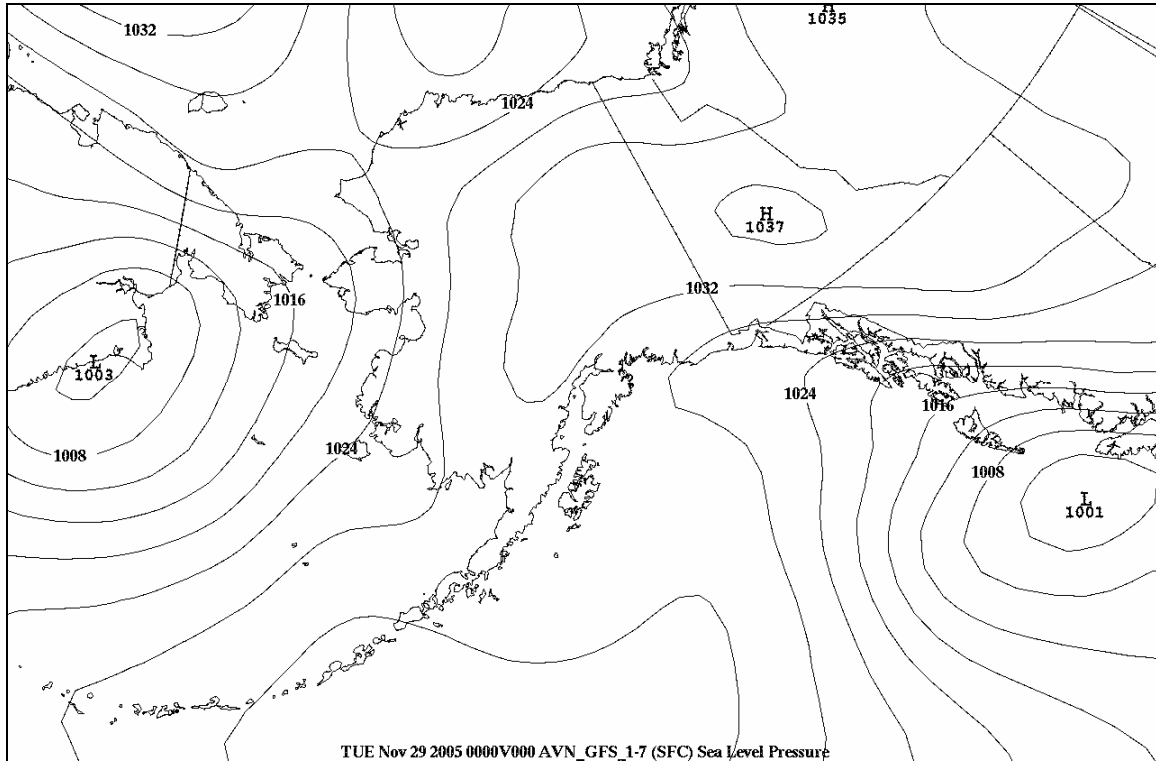


Figure 8. Sea-level pressure analysis for AK on 29 Nov 05 at 00Z. From NCEP/NCAR, 2007.

On the last day of the event, the pressure gradient strengthened once again over the base, and the winds became much more northerly in response to a new low pressure center to the west and a deepening of the trough over the base. An induced ridge along the Aleutian Chain formed by 00Z on 29 Nov (Fig. 8). A weak low pressure area near Nome, AK was also beginning to move to the southeast at this time period, and was inevitably responsible for inducing precipitation towards the end of the day on 30 Nov into the morning of 1 Dec, as vertical velocities increased in response to positive vorticity advection.

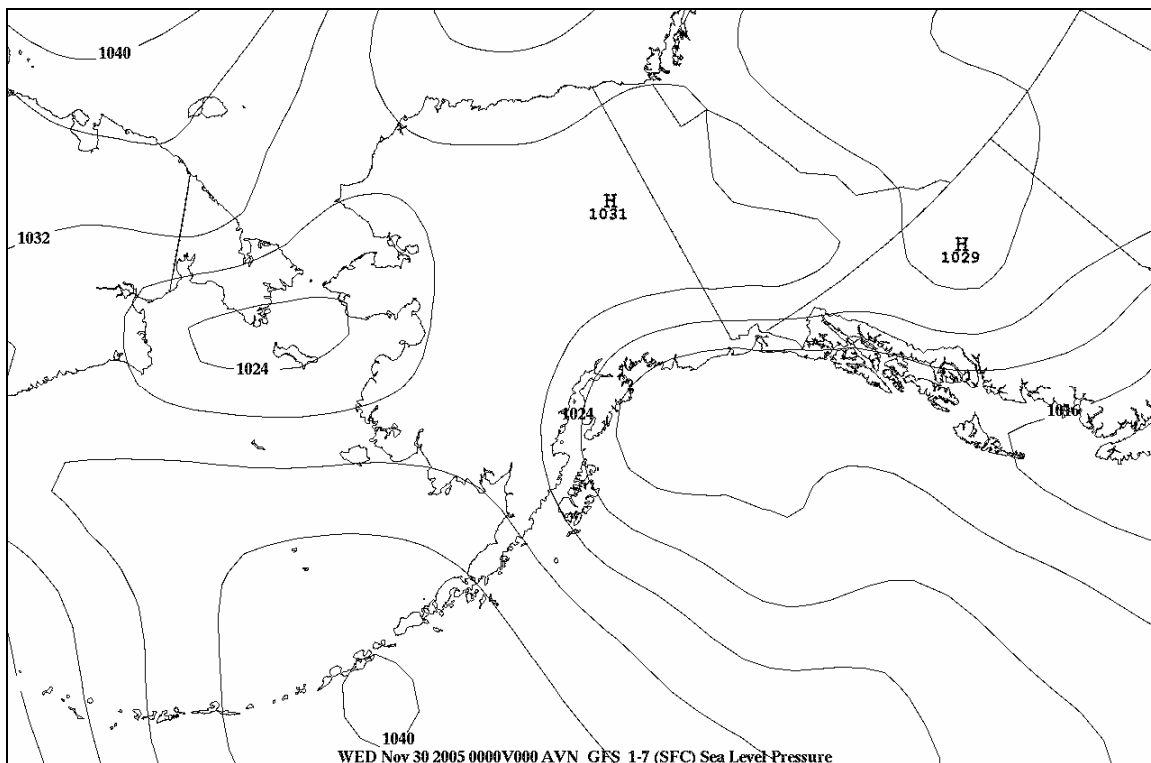


Figure 9. Sea-level pressure analysis for AK on 30 Nov 05 at 00Z. From NCEP/NCAR, 2007.

2. Observational Analysis

Observations late in the day on 27 Nov started to change, with a sharp increase in temperatures after sunrise (1830Z), and a rapid drop in visibility (indicated by the line in Fig. 10). This impact was short lived, and was believed to be associated with a weak mixing of the nearly saturated boundary layer at sunrise. The pressure was on the rise throughout the day, and winds remained northeasterly and light until 20Z, when they shifted slowly out of the north. At the same time of this wind shift, a thin and widely scattered stratus deck was observed, and within 3 hours of its arrival, the visibility dropped to 1/2 SM with freezing fog. The water level shows that this time correlated strongly with high tide, where a maximum water level of 27.5 ft had occurred (Fig. 11).

Coincidentally this was only 15 minutes before a stratus deck appeared over the base at 200 ft, and visibilities were reported to be 1/2SM.

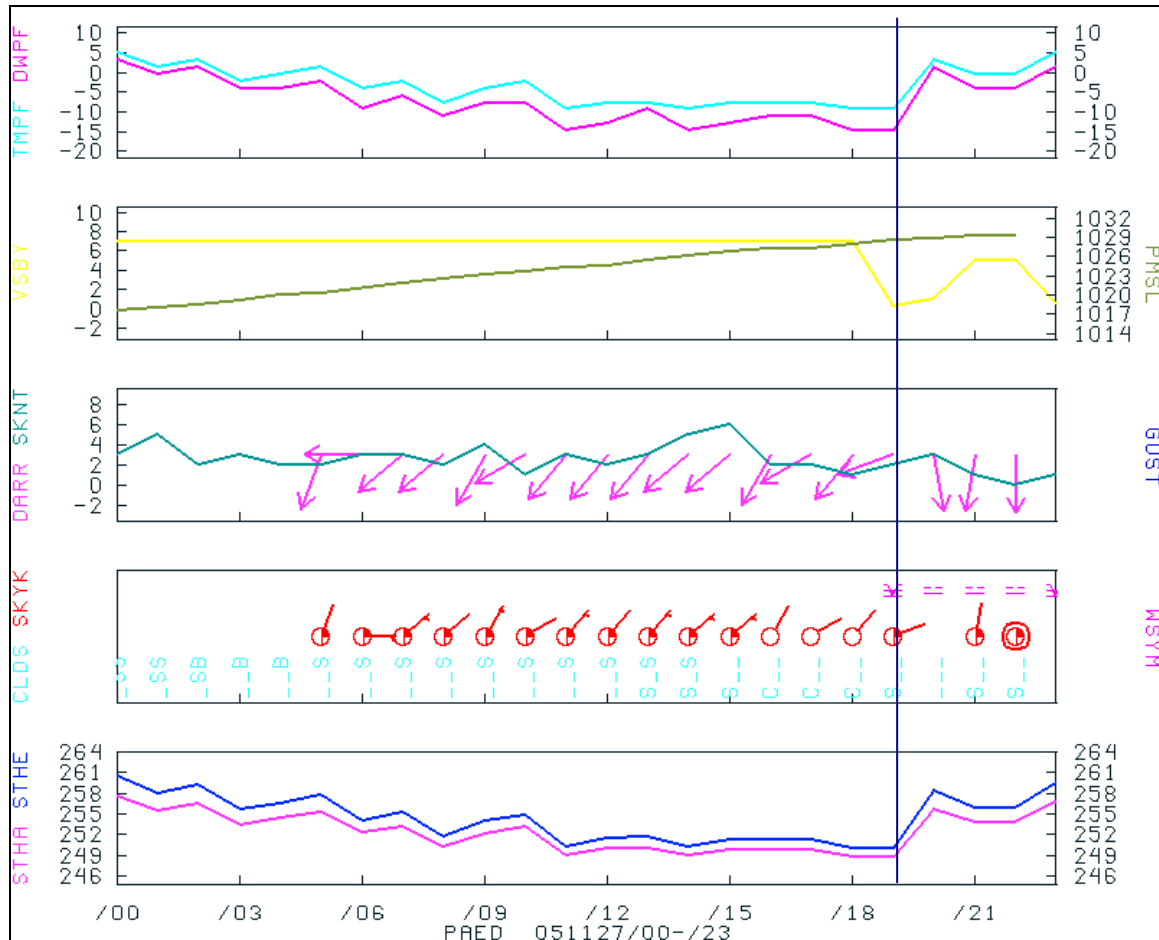


Figure 10. Meteogram for PAED on 27 Nov 05. The meteograms have 5 blocks that depicts 12 different variables). Block 1. shows the temperature in Fahrenheit (TMPF), and the dew point temperature in Fahrenheit (DWPF). Block 2 shows the visibility in statute miles (VSBY) and the mean sea level pressure (PMSL). Block 3 shows the wind direction as a vector (DARR), the wind speed in knots (SKNT) and the wind gusts in knots (GUST). Block 4 shows the cloud cover at 3 levels (low, mid, upper) by type of cover (CLDS), the sky cover with wind barbs (SKYK), and the restriction to visibility (WSYM). Block 5 shows the surface potential temperature (STMA) and the surface equivalent potential temperature (STHE). From NCEP/NCAR, 2007.

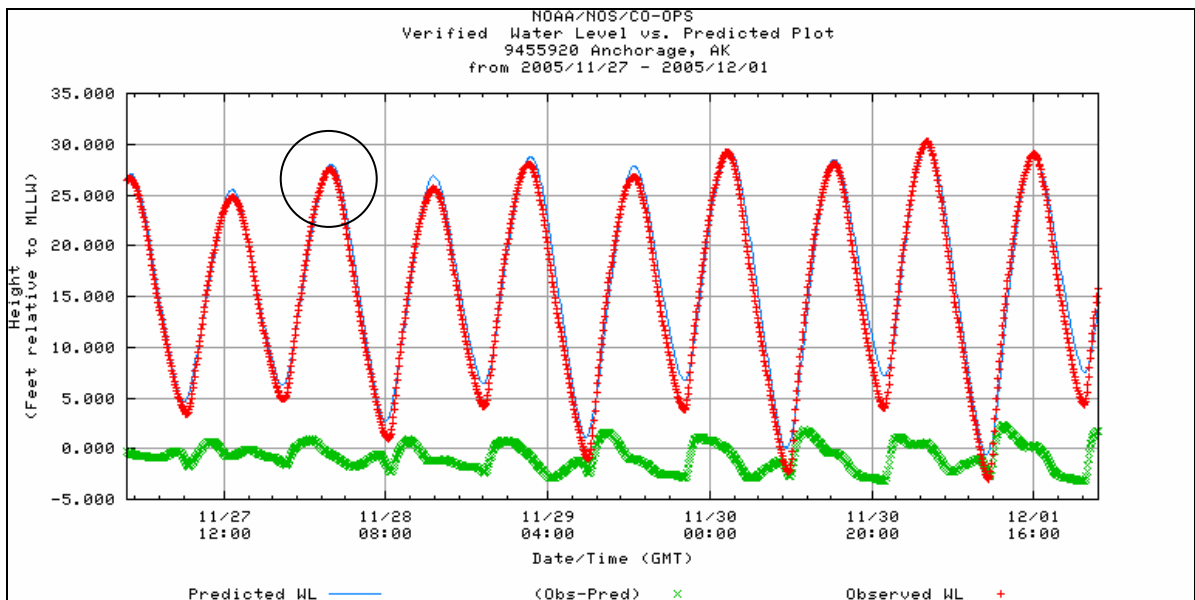


Figure 11. NOAA plot of water level vs. predicted water level for Anchorage, AK (Cook Inlet) for the period from 27 Nov-01 Dec 2005. From NOAA, 2007.

After 2046Z on 27 Nov, the visibility restrictions lasted for the following 26-hours, until 18Z on 28 Nov. During this long stretch of reduced visibilities, 8 hours reported 1/16 SM visibilities, with only 5 hours reporting 3 SM or greater. This meant that nearly 80% of the day required pilots to fly by Instrument Flight Rules (IFR), and 30% of the day had visibilities that would have prevented any take-offs or landings based on Air Force Instruction.

There appeared to be a correlation between the wind and the onset of freezing fog, since the winds at the time of the fog formation suddenly increased to 4 kts and were from the northeast (Fig. 12). However, special observations showed that the fog formed nearly 1 hour before the winds began to blow from the northeast, and that winds were actually calm at the time of the onset of fog. One explanation is that the winds were drainage winds, which were ultimately responsible for advection of fog to the base.

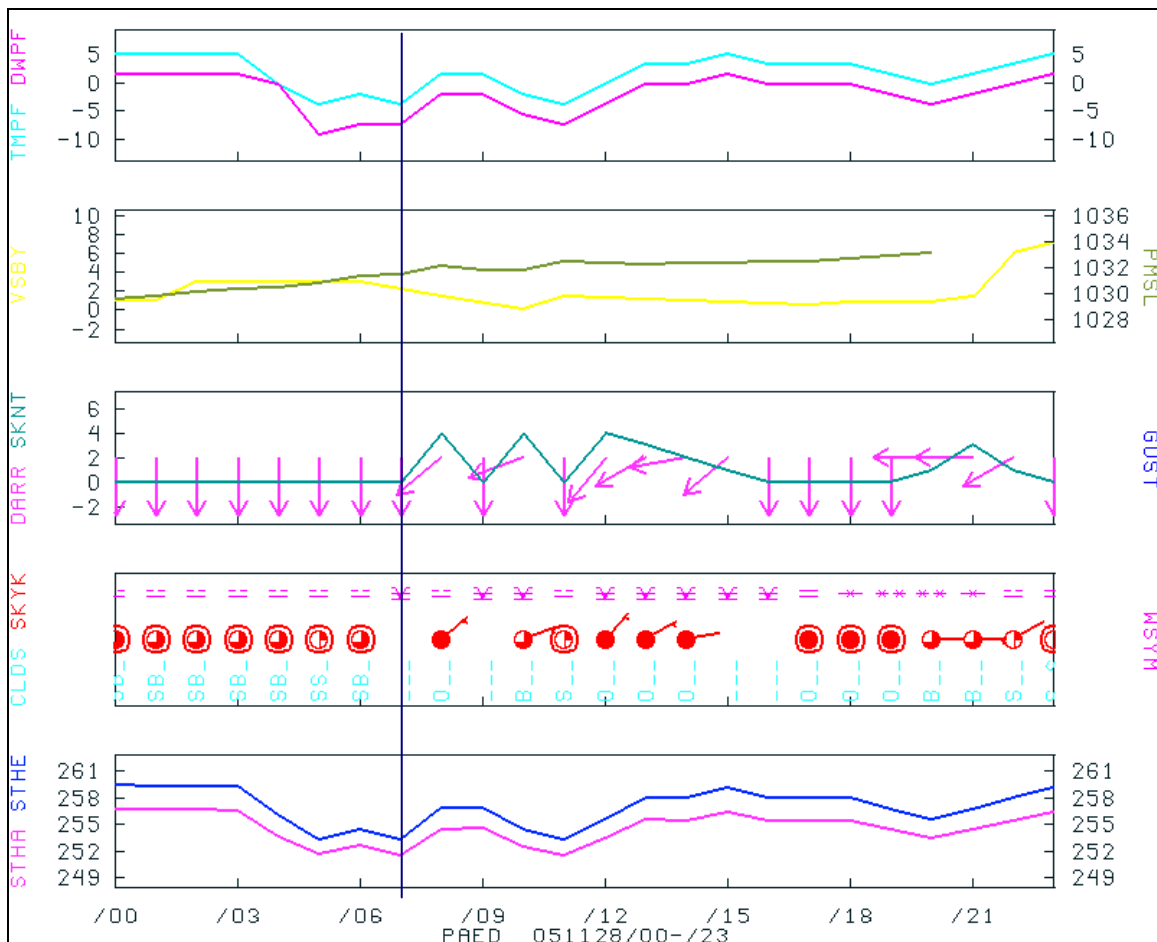


Figure 12. Meteogram for PAED on 28 Nov 05. From NCEP/NCAR, 2007.

The most fascinating phenomena was the drastic change in the temperature and dew point temperature that occurred coincidental to fog being observed. The initial temperature and dew point temperature drop between 05Z and 06Z occurred at a time after sunset, when cooling should have been occurring due to radiational loss at the surface. While there was cloud cover present in the low levels, it was thin enough to presumably not produce enough incoming longwave radiation to counteract the losses from the surface. But the reason for the strong rise in temperature and dew point temperature between 06Z and 07Z was hard to explain. Since the visibility at 0636Z (indicated by the line in Fig. 12) suddenly went down to 1/16 SM from 3 SM, and sudden warming

and moistening occurred, it is believed that the local air mass changed as a result of fog entering the base. There is also the possibility that this warming was induced by a weak mixing from the level where the stratus was, which had a warmer temperature based on sounding data (as seen later in Figs. 16 and 17).

By 23Z on 28 Nov, the visibility was back up to 7 SM for only 2.5 hours, before going down to 1/8 SM again at 0144Z on 29 Nov (indicated by the line on the left in Fig. 13). At the time that the visibility decreased, the wind started to blow from the due east, albeit lightly. The visibility this time stayed down to at or below 1 SM for 18 hours before rebounding again for only 2 hours (indicated by the line on the right in Fig 13). The fog both days seemed to burn-off just after sunrise, which dynamically makes sense. And since there is very little available sunlight during the winter months, a burn-off would be short-lived, but would be expected to occur around midday if it did. While the visibility stayed down throughout the day, ice crystals were also reported, which did not occur on 28 Nov. These ice crystals are thought to be the result of strong cloud top cooling, which froze water droplets at the top of the boundary layer. These crystals then settled, and as a previous study showed, the fall rate and mass of ice crystals is greatest at -18°C , which coincidentally, was the average temperature for most of the day on 29 Nov. What impact the ice crystals had on maintaining saturation at the surface is unknown, but there appeared to be a correlation between ice crystals being observed, and the persistence of freezing fog in this region. When all was said and done, there were a total of 45 out of 72 hours that reported a visibility of 1 SM or less due to freezing fog, with the lowest being 0 SM at 0516Z on 29 Nov.

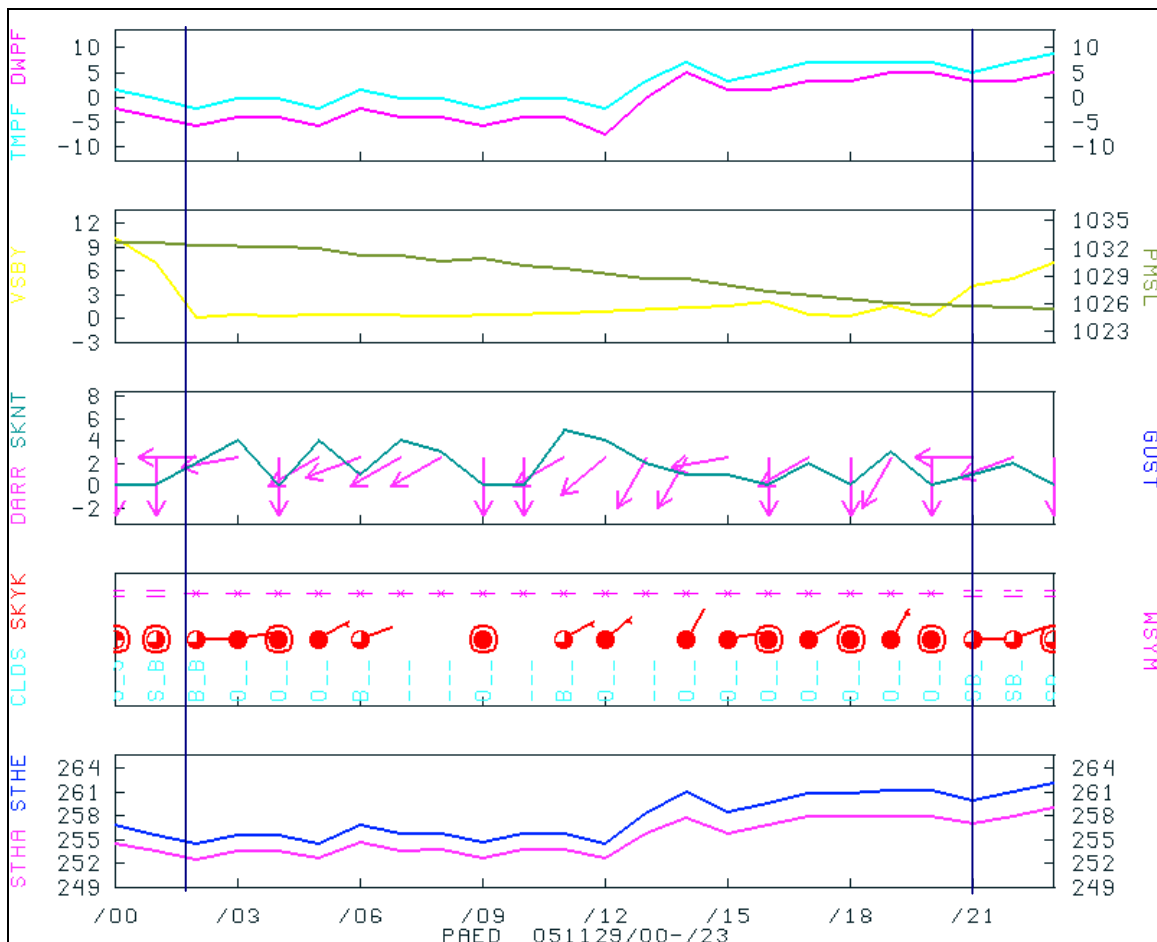


Figure 13. Meteogram for PAED on 29 Nov 05. From NCEP/NCAR, 2007.

3. Sounding Analysis

Beginning with data on 27 Nov, a trend in the lowest portions (surface-975mb) of the boundary layer was noted. The relative humidity values within this defined level rose drastically, which would be expected in a fog case. At 00Z on 28 Nov, RH value at 1023mb was 88% (Fig. 14). As it turns out, the strongest increase took place just above this level, from 1013mb-993mb (or 141m-297m above ground level (AGL)). The relative humidity at 1026mb (the lowest data point) according to the RAOB data from Anchorage at 12Z on 28 Nov, was 88% with a temperature of -14.7°C and a dew point of -16.3°C (Fig. 15), while the observation from PANC showed a surface temperature of -17°C and a dew point

temperature of -19°C at this same time. The implication was that in the lowest 40m of the boundary layer (from surface to 1026mb), there was a 3°C rise in temperature and a 3°C rise in dew point temperature (with an assumed minimal error resulting from sensor differences). This indicated that a strong, surface-based inversion was present due to radiational cooling at the surface, and that the fog could have been the result of the rapid cooling at the base of the boundary layer, forcing moisture to condense. However, after looking at the levels just above the surface, there was a notable increase in both moisture content, and a change in the wind direction. Initially, it was unclear what to make of this amount of moisture increase just above the surface. Radiation fog events typically have moisture limited to the lowest 30 m (100 ft) of the atmosphere (www.srh.noaa.gov). In this event, the highest moisture level was 125-280 m (450-900 ft) above the surface (or in the stratus deck that was overhead). So while enough cooling took place to potentially saturate the boundary layer, it did not appear that the moisture at the surface was enough to create condensation, and that moisture may have been “seeded” from above.

70273 PANC Anchorage Observations at 00Z 28 Nov 2005										
PRES hPa	HGHT m	TEMP C	DWPT C	RELH %	MIXR g/kg	DRCT deg	SKNT knot	THTA K	THTE K	THTV K
1023.0	40	-13.9	-15.5	88	1.12	330	2	257.6	260.7	257.8
1008.0	158	-14.1	-15.8	87	1.11	330	4	258.5	261.5	258.6
1000.0	221	-13.1	-19.1	61	0.85	330	5	260.1	262.4	260.2
989.0	305	-13.3	-19.3	61	0.84	332	5	260.7	263.1	260.8
953.0	590	-8.7	-18.7	44	0.92	339	5	268.1	270.8	268.3
950.5	610	-8.7	-18.8	44	0.91	340	5	268.4	271.0	268.5
925.0	821	-8.3	-20.3	37	0.83	5	6	270.8	273.3	270.9
914.0	914	-8.0	-20.8	35	0.80	15	6	272.1	274.5	272.2
911.0	940	-7.9	-20.9	34	0.80	16	6	272.4	274.8	272.5
903.0	1008	-6.1	-25.1	21	0.56	20	6	274.9	276.7	275.0
878.9	1219	-7.5	-26.1	21	0.52	30	6	275.6	277.2	275.7
850.0	1479	-9.3	-27.3	22	0.48	105	2	276.4	277.9	276.5

Figure 14. RAOB data from 00Z on 28 Nov 2005. From UWSP, 2007.

70273 PANC Anchorage Observations at 12Z 28 Nov 2005										
PRES hPa	HGHT m	TEMP C	DWPT C	RELH %	MIXR g/kg	DRCT deg	SKNT knot	THTA K	THTE K	THTV K
1026.0	40	-14.7	-16.3	88	1.05	0	0	256.6	259.4	256.7
1013.0	141	-12.9	-12.9	100	1.41	346	1	259.3	263.1	259.5
1000.0	243	-12.9	-13.0	99	1.41	331	1	260.2	264.1	260.5
993.0	297	-12.9	-13.0	99	1.42	323	2	260.8	264.7	261.0
979.0	405	-10.7	-16.7	61	1.06	307	2	264.1	267.1	264.2
947.0	662	-6.9	-19.9	35	0.84	270	4	270.4	272.9	270.6
925.0	846	-6.1	-19.1	35	0.92	244	5	273.1	275.8	273.2
882.0	1218	-7.3	-21.3	32	0.80	190	7	275.6	278.0	275.7
881.8	1219	-7.3	-21.3	32	0.80	190	7	275.6	278.0	275.7
854.0	1468	-9.5	-15.5	62	1.35	199	7	275.8	279.8	276.0
850.0	1504	-9.7	-15.7	62	1.33	200	7	276.0	279.9	276.2

Figure 15. RAOB data from 12Z on 28 Nov 2005. From UWSP, 2007.

In the 975-925mb layer, dry air was present at the top of the fog layer at 00Z on 28 Nov (Fig. 16), helping to promote evaporation, and allowing cooling to take place. This layer continued to remain dry into 12Z on 28 Nov (Fig. 17), which likely helped to maintain the condensation process at the top of the layer through evaporational cooling. It also may have been responsible for the formation of ice crystals, as was alluded to in the previous section. While the exact source region of the ice crystals was unknown, it is likely that they were forming around 950mb due to the cloud top evaporational cooling that was helping to freeze some of the water droplets at the top of the cloud.

Within the 925mb-850mb layer, dry air was in place at the beginning of the period, but for a brief 12 hour stint between 12Z on 28 Nov and 00Z on 29 Nov, moistening occurred (and can be seen as a spike in the dew point profile at 850mb in Fig. 17). RH values on average within the level went from 32% to 71% during this time period, and the winds shifted from 020 to 220. Winds from a 220 direction were from the mP air mass over the Gulf of Alaska, which was much warmer and moister than the air mass in place. After this time, the wind quickly shifted back around to the north, and the RH values coincidentally decreased rapidly back to the 30% range.

70273 PANC Anchorage

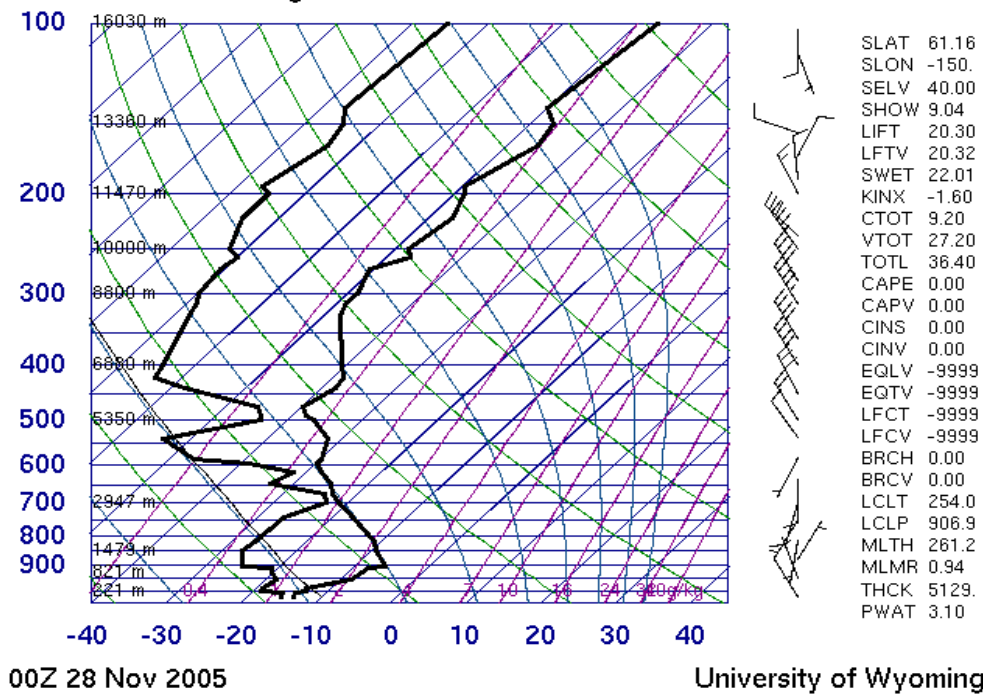


Figure 16. Upper-air sounding from PANC launched at 00Z on 28 Nov 2005.
From UWSP, 2007.

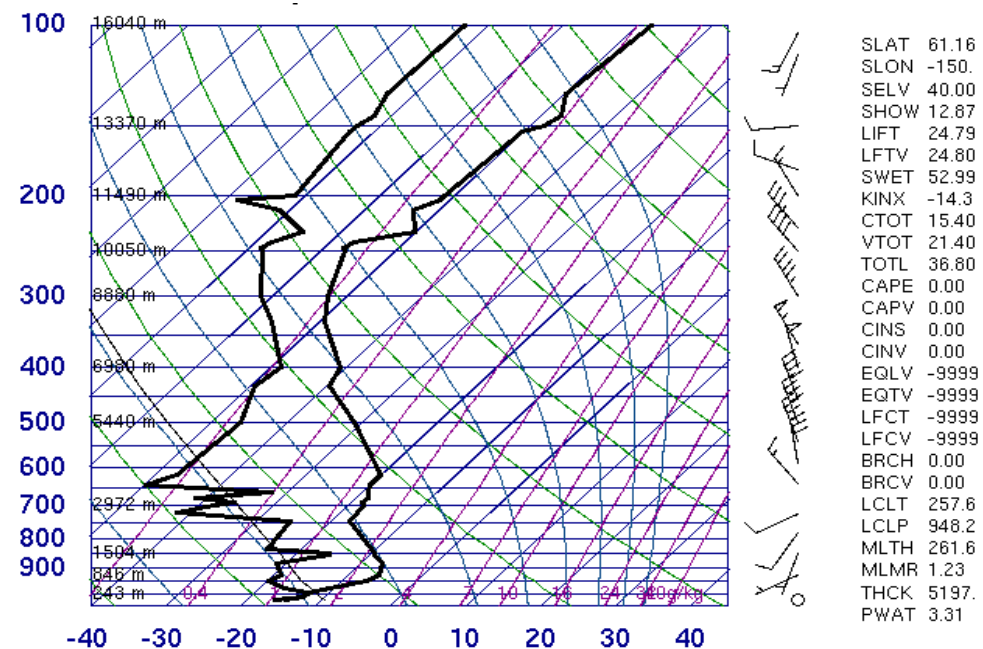


Figure 17. Upper-air sounding from PANC launched at 12Z on 28 Nov 2005.
From UWSP, 2007.

4. Case Summary

In review, case 1 started off with a synoptic high pressure system in place that was weakening in response to a trough retrograding towards the region from the southeast. Winds were relatively light, and a cold air mass had just made its way into the Anchorage Peninsula from the north. Shortly before the onset of fog, high tide occurred, and a stratus deck appeared, which coincidentally was observed when the freezing fog was reported. The freezing fog started off intermittently on 27 Nov, but by 0636Z on 28 Nov was in full throat. The duration of the fog event was on the order of 48-hours, with the heaviest restrictions to visibility occurring in the early morning hours, and were as low as 1/16 SM, while the visibility improved slight after sunrise each day. Moisture advection was noted in the level from 141m -297m, and coincided with a stratus deck that was reported throughout the event. Ice crystals also began to be observed during periods of freezing fog on 29 Nov.

The impact of the stratus on fog formation was determined to be relevant, since the timing of the fog and the presence of stratus were correlated. While the exact extent could not be determined, the observations and soundings highlighted that moisture advection was strongest in the levels just above the surface, and that low level moisture was present during the entire event. Radiational cooling also appeared to be a strong factor in creating a cold enough surface air mass to force moisture to condense, but the moisture did not appear to be substantial enough on base to create fog. The fog likely formed at the base of the mountains, and was “forced” towards the base by cold drainage flow. This slightly warmer and more moist air mass made its way towards the base, and helped to increase the temperature and dew point temperature.

C. CASE 2 (4 DECEMBER 2005)

Only three days after the end of the last case, another fog outbreak occurred. The synoptic pattern was similar to that of the previous event, although at this point, the low pressure system from the Gulf of Alaska was just

east of the base, and had deepened a bit. The pressure gradient was again fairly strong over the base, and the associated winds above the surface were from the north, helping to advect a secondary cold blast of air into the region, taking the temperature back below the climatological mean. Prior to the fog forming, mid-level cloud cover was present, and the temperature dropped drastically (from -11°C to -19°C) and drier air had moved into place at the surface. A stratus deck formed at 0715Z on 04 Dec, and fog developed seemingly instantaneously. The fog lasted for the duration of the day, with light snow reported for a few hours just after the fog formed. By 5 Dec, the stratus deck rose to 500 ft, and the freezing fog dissipated in conjunction with more persistent snow fall.

1. Synoptic Overview

At the start of the period, the low pressure center was at 1000mb, and was located approximately 130 Nautical Miles (NM) to the east of Elmendorf AFB. The pressure gradient from this major shortwave system was strong enough that winds in the mid-levels were on the order of 50 kts and higher. There was an extremely strong high pressure center over Siberia (1052mb) that was creating a strong gradient along the west coast of AK. This strong arctic high pressure system collapsed southward into northern AK on 5 Dec., forcing the associated pressure gradient to become more zonal from northwest to southeast and causing the weather to deteriorate, and as fog gave way to snow, winds at the surface began as weak and northerly, and didn't change much until 5 Dec, when they shifted to southeasterly.

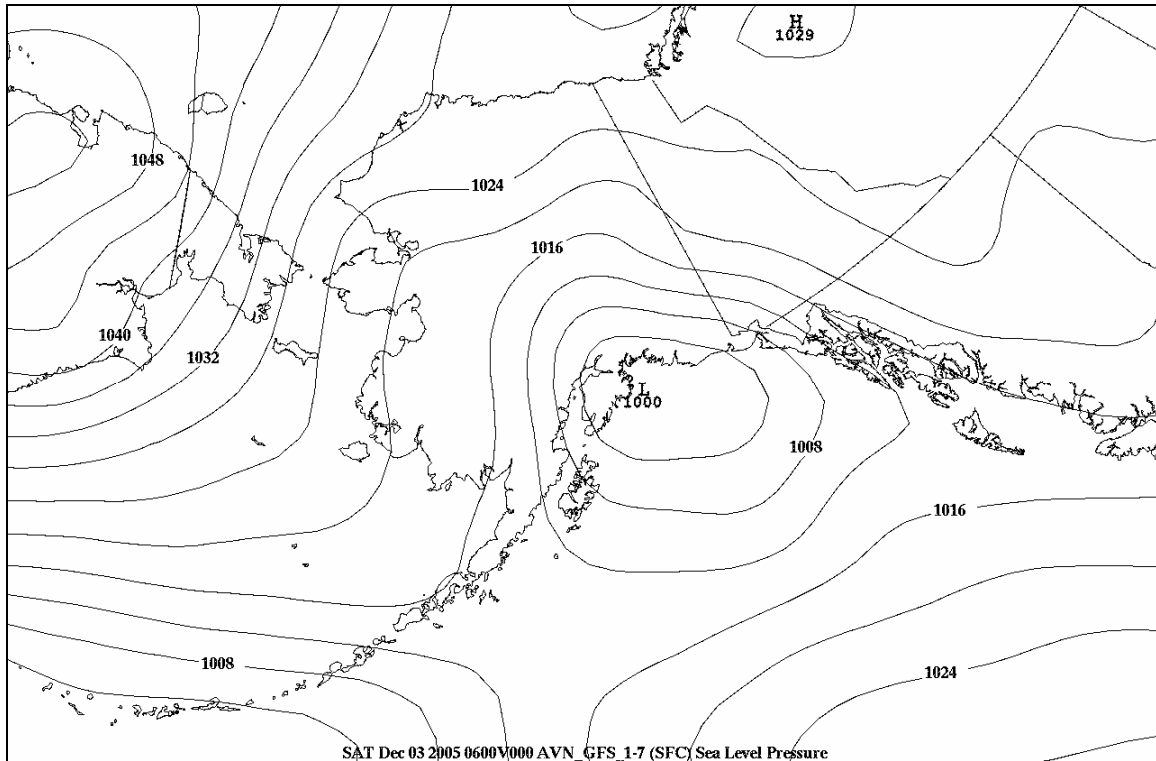


Figure 18. Sea-level pressure analysis for AK on 03 Dec 05 at 06Z. From NCEP/NCAR, 2007.

The pressure pattern on the day before the fog formed showed a low pressure influencing the weather along the southern coast of Alaska, while an induced ridge to the northwest was influencing the interior region (Fig. 18). An even stronger ridge was developing along the west coast, associated with a strengthening Siberian High. The interaction between the low and the two highs was creating a northeastern wind component over the base. The synoptic air mass during this time period was cP, and temperatures on the north side of the Alaskan Range (from where the surface wind was blowing) were some 20°C colder than the air near the base (observations showed that Fairbanks, AK was at -39°C).

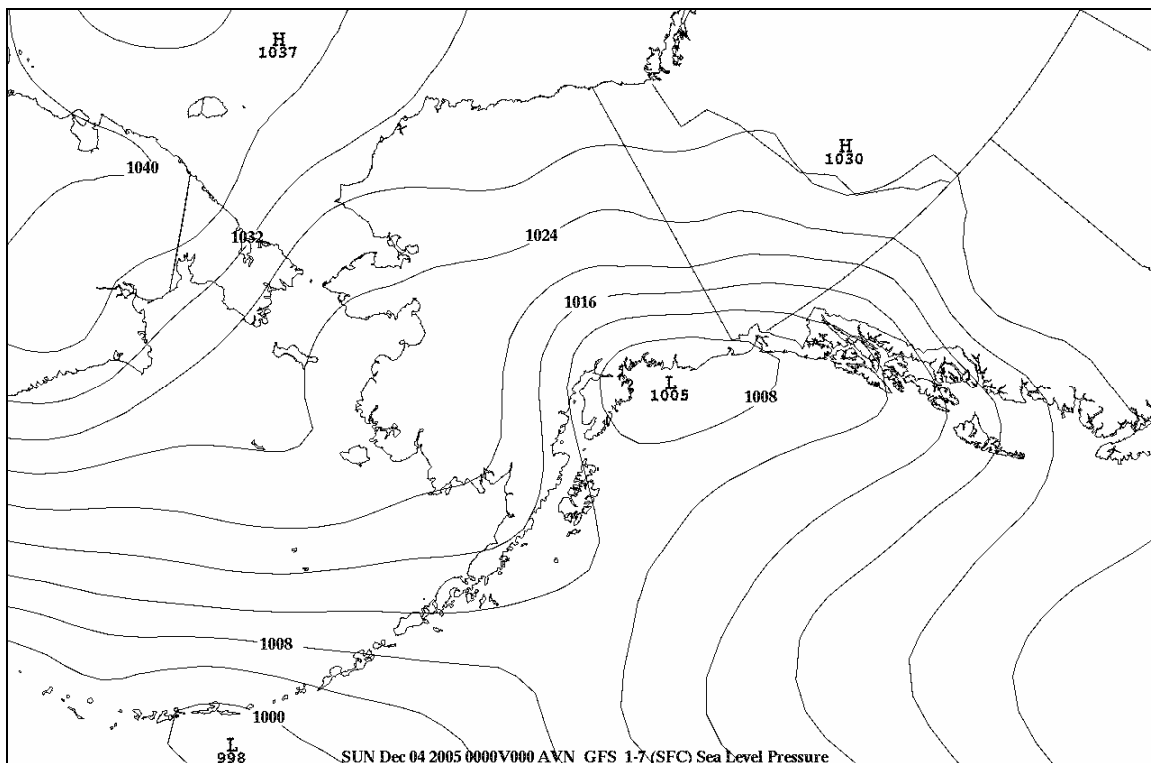


Figure 19. Sea-level pressure analysis for AK on 04 Dec 05 at 00Z. From NCEP/NCAR, 2007.

Not much change had occurred in the pressure analysis between 03 Dec and 04 Dec. The low pressure center near the base had weakened a bit and moved ever-so-slightly off to the northeast, while the ridge to the west had also weakened a bit. The pressure at the base was rising, and the pressure gradient was slowly shifting to create a more northerly wind component for the forecast region. The orientation of the occluded low (Fig. 19) to Elmendorf AFB put the base in the area of the low where the cold conveyor belt would be expected to bring cold air to the surface from aloft, which could have caused some of the compacting of the boundary layer. This was verified by the upper-air profiles.

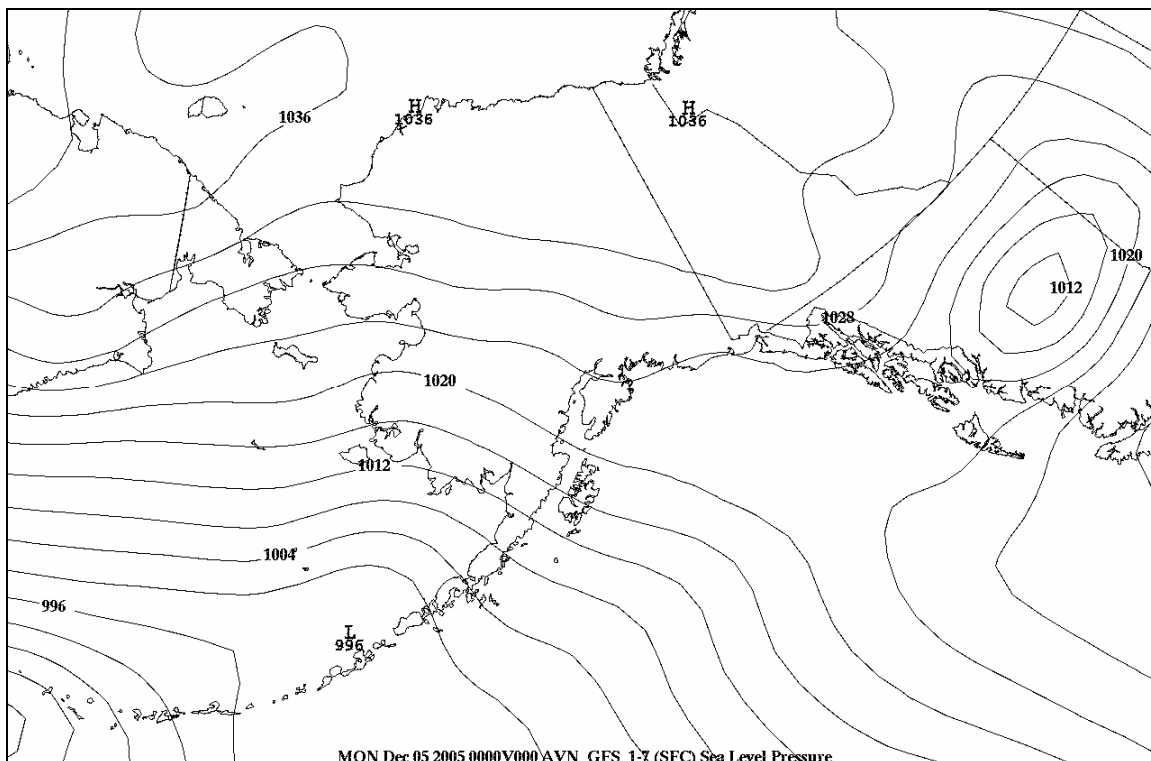


Figure 20. Sea-level pressure analysis for AK on 05 Dec 05 at 00Z. From NCEP/NCAR, 2007.

By 05 Dec, the pattern had changed significantly from just 24 hours before, with the low getting kicked out into British Columbia, and the strong ridge building into the west coast of Alaska (Fig. 20). The flow was now more zonal, and the wind at the surface from the southeast. By midday, snow began to fall at the base, and the synoptic pattern had changed significantly enough that fog did not return to the base for nearly a month.

2. Observational Analysis

On 3 Dec, weather conditions were fairly benign (Fig. 21). Light snow had fallen early in the morning, but stopped, and gave way to mostly cloud skies and unrestricted visibility. A stratus deck hung around at 2000 ft, and temperatures

rose from -20°C to -11°C during the daylight hours. Nothing in the observations on 3 Dec was indicative of the forthcoming fog event that would take place only hours into 4 Dec.

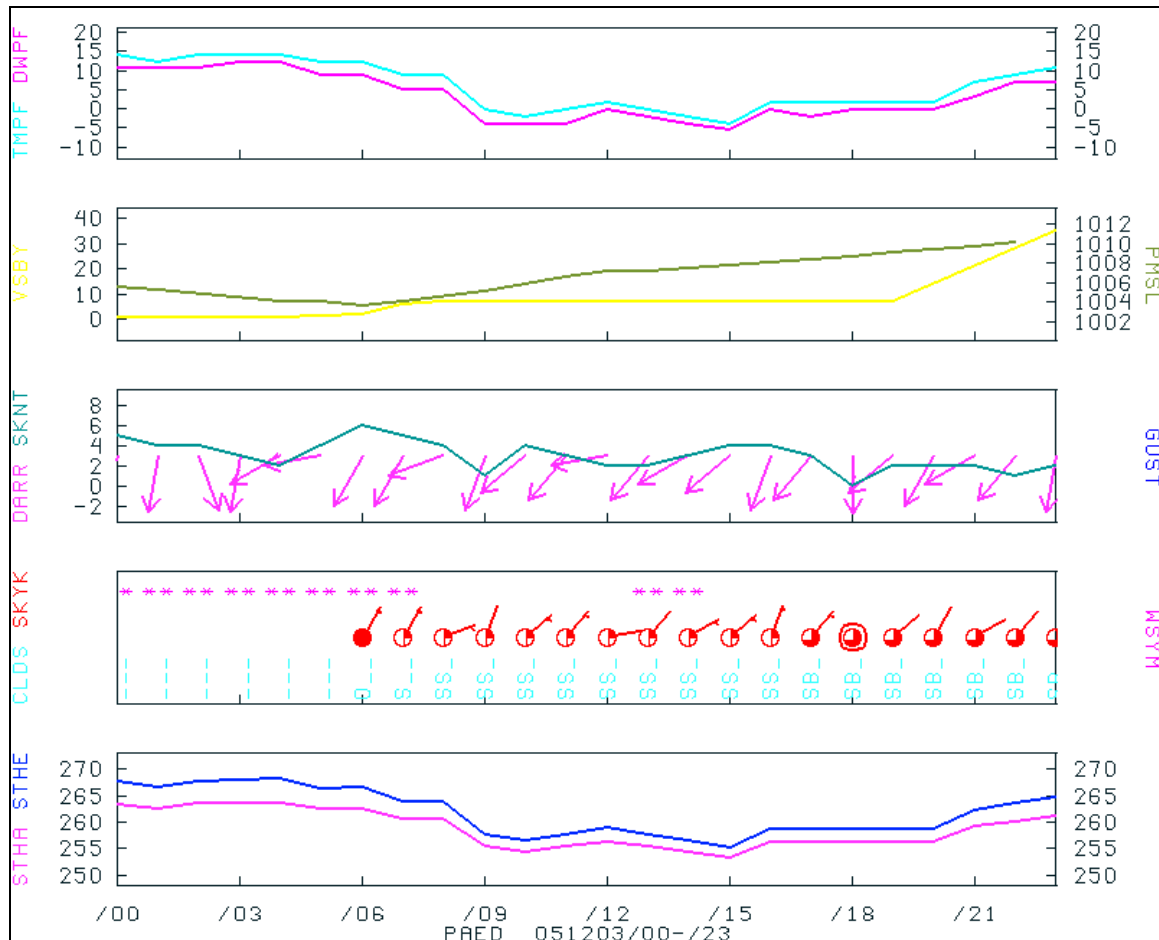


Figure 21. Meteogram for PAED on 03 Dec 05. From NCEP/NCAR, 2007.

On 4 Dec, the temperature dropped fairly rapidly, as would be expected from diurnal temperature changes due to radiational cooling. The dew point also dropped at the same rate, although continued to fall, while the temperature leveled off by 04Z. At 06Z and at 09Z, the temperature and the dew point temperature suddenly jumped (indicated by the 2 lines in Fig. 22), and a stratus deck was observed associated with the first spike, along with freezing fog shortly thereafter. Comparing the water level data with that of the stratus deck, it

appeared as if there was a strong correlation between the timing of the stratus and fog, and the amount of water available from high tide (indicated by the circle in Fig. 23).

It is believed that the temperature and dew point temperature increases were the result of the onset of the fog itself, and not from advective processes. With the amount of radiational cooling that took place before the fog, it is likely that the air mass in place was much cooler than that of case 1. This would have allowed the moisture from the flux of water during high tide to condense much closer to the ground, than the last event. Since there was no apparent wind shift during this event, it is believed that the fog actually formed on station, and that the primary source of moisture and heat came from the open water at high tide. A secondary (and much smaller) effect was likely that of condensational heat release. While this is not likely significant, it certainly has to be noted as a feasibility.

The reason for the second warming was not clear, since there was no apparent horizontal change that occurred. There was cold air advection that occurred just above the surface (as is seen later in Figs. 26 and 27), and could have come from on the leeward side of the Chugach range. This could have created enough mixing and cooling just above the surface to compress the boundary layer. While compression is inherently a warming process, and could have reduced the thickness of the layer, it could have also helped to strengthen the inversion, and allowed for enhanced condensation below the inversion. A second scenario could have been correlated to the sudden appearance of ice crystals. It is believed that ice crystals formed at the top of the cloud deck as a result of strong cold and dry air advection that occurred between 925-850mb (as seen in the soundings for this time period). If enough cold air was available above and moist air available below, it is possible that ice crystals formed at the interface between the cloud and the dry air above the cloud. Once ice crystals had formed, they inevitably would have settled through time. So it is feasible that not only were the ice crystals partially responsible for warming the air through

subtle latent heat releases, but that they also came from a portion of the cloud that was warmer (near the inversion), and were transported to the surface through mixing, which would support the case that sinking air from the mid-levels helped to compress the boundary layer. Whatever the case may have been, the sudden warming and moistening, and the onset of ice crystals correlated well during this event.

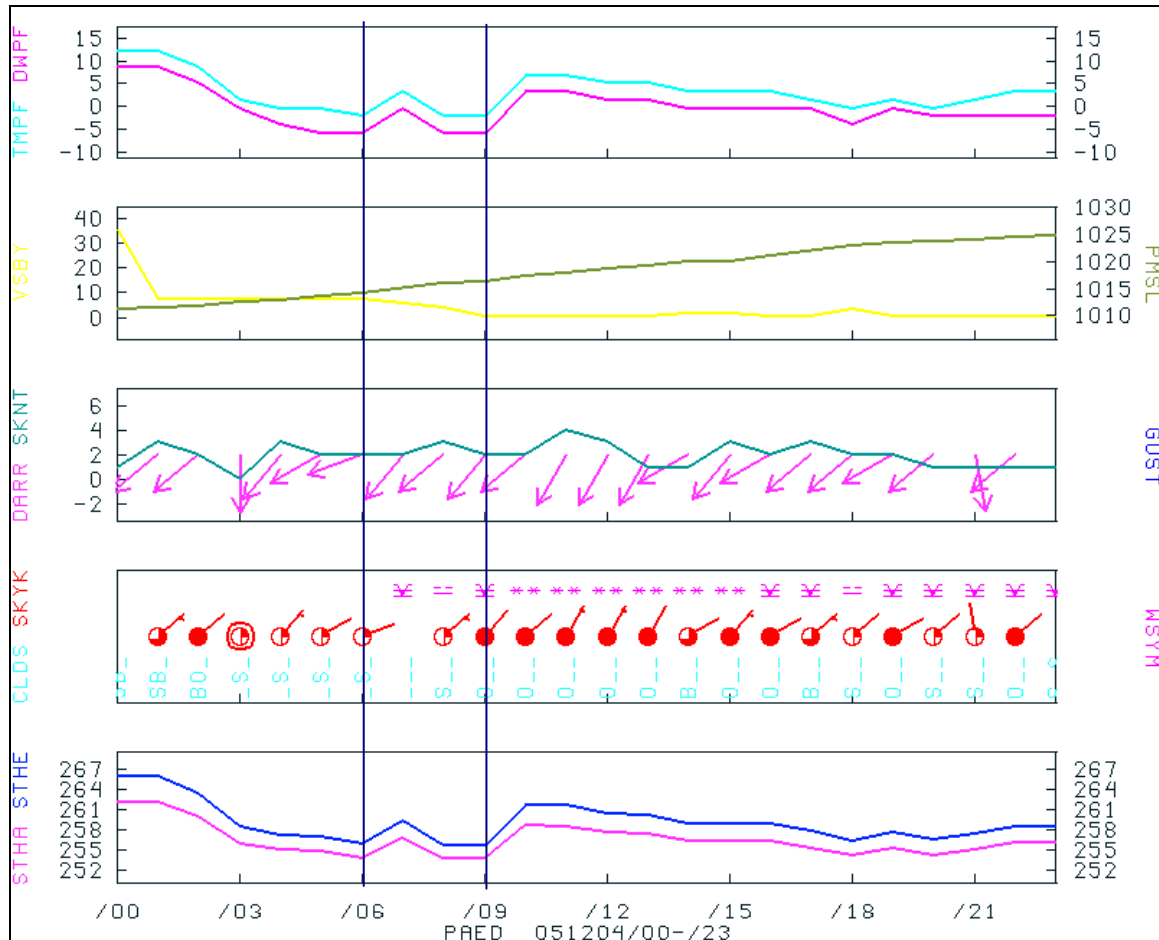


Figure 22. Meteogram for PAED on 04 Dec 05. From NCEP/NCAR, 2007.

In a high resolution image of the area, a line of stratus was seen lying up against the Chugach Range (Fig. 24). While PAED was still reporting freezing fog at this time, it had diminished in thickness.

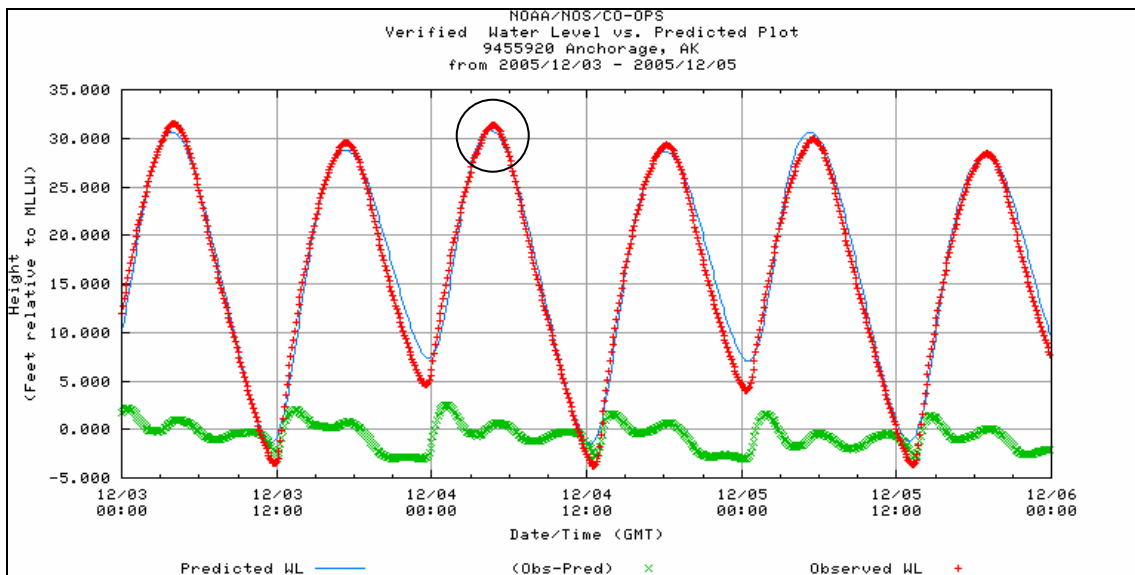


Figure 23. NOAA plot of water level vs. predicted water level for Anchorage, AK (Cook Inlet) for the period from 03 Dec-06 Dec 2005. From NOAA, 2007.



Figure 24. Aqua-Modis 250m High Resolution visible image taken at 2135Z on 4 Dec 2005. From MODIS Rapid Response, 2007.

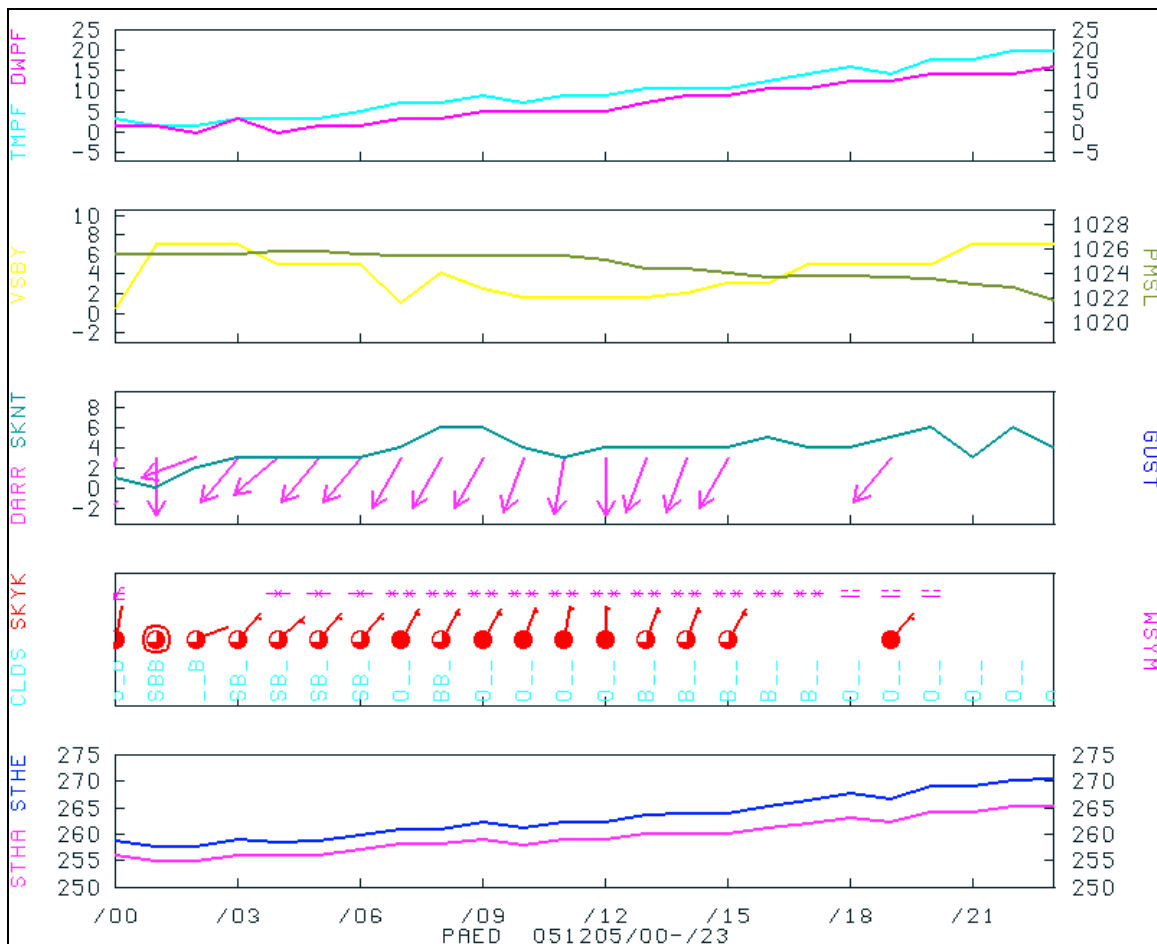


Figure 25. Meteogram for PAED on 05 Dec 05. From NCEP/NCAR, 2007.

The visibility increased drastically on 5 Dec at 00Z (Fig. 25), and remained high when snow was not falling. The temperature and dew point temperature were slowly on the rise as an air mass change had occurred, and a mP air embedded itself into the region. The winds picked up a bit to near 6 kts, which presumably kept the boundary layer from saturating because of the destructive horizontal mixing. The fog at Elmendorf AFB had ended, and would not come back again for nearly an entire month.

3. Sounding Analysis

Beginning with analyses of the temperature and dew point temperature in the RAOB data, it appeared that a fairly significant radiational inversion had set up. There was a slight moistening of the lowest level, but not to the extent of that in case 1. Within the surface-975mb level, the mixing ratio maintained a greater than 1.2 g/kg value (Fig. 26 and Fig. 27), and was consistent within the layer, not like in the previous case where the main plume of moisture appeared to be confined to a layer from 150-300m above the surface. This vertically homogeneous layer led to the conclusion that the fog likely formed spontaneously over the entire region, and did not drain from the east in this event. RH values increased dramatically in the layer from 1000mb-975mb, although the mixing ratio did not (Fig. 26).

70273 PANC Anchorage Observations at 00Z 04 Dec 2005										
PRES hPa	HGHT m	TEMP C	DWPT C	RELH %	MIXR g/kg	DRCT deg	SKNT knot	THTA K	THTE K	THTV K
1004.0	40	-11.9	-13.2	90	1.38	30	2	260.9	264.8	261.2
1000.0	82	-12.1	-13.4	90	1.37	26	2	261.1	264.8	261.3
984.0	205	-12.9	-14.1	91	1.31	8	3	261.4	265.1	261.7
973.0	291	-12.7	-16.0	76	1.13	356	3	262.5	265.7	262.7
925.0	675	-14.3	-19.3	66	0.90	300	5	264.7	267.3	264.8
912.0	782	-15.1	-21.1	60	0.78	311	5	264.9	267.2	265.1
896.2	914	-15.4	-20.4	65	0.84	325	5	266.0	268.4	266.1
860.8	1219	-16.0	-18.9	78	1.00	10	6	268.4	271.4	268.6
853.0	1287	-16.1	-18.6	81	1.04	21	6	269.0	272.0	269.2
850.0	1314	-15.3	-17.8	81	1.12	25	6	270.1	273.4	270.3

Figure 26. RAOB data from 00Z on 04 Dec 2005. From UWSP, 2007.

At the next level of the boundary layer (975mb-925mb) the mixing ratio started out at 1.1 g/kg, but dropped quickly below 1.0 g/kg by 12Z on the 3 Dec. It stayed right around 1.0 g/kg throughout this layer until 5 Dec, when it suddenly jumped to 2.5 g/kg (and snow began to fall). The drying early on in the period was attributed to winds that were westerly (270-320), where a slightly cooler and

drier air mass was in place. The winds also increased to nearly 10kts. This cold dry air could have been mixed to the surface during the early hours of 4 Dec.

70273 PANC Anchorage Observations at 12Z 04 Dec 2005										
PRES hPa	HGHT m	TEMP C	DWPT C	RELH %	MIXR g/kg	DRCT deg	SKNT knot	THTA K	THTE K	THTV K
1012.0	40	-14.1	-15.7	88	1.12	0	1	258.2	261.2	258.3
1004.0	105	-14.3	-14.3	100	1.27	3	1	258.6	262.0	258.8
1000.0	137	-14.5	-14.5	100	1.25	5	1	258.6	262.1	258.9
992.0	198	-13.5	-13.5	100	1.37	9	1	260.2	264.0	260.5
978.1	305	-13.1	-15.6	82	1.17	15	1	261.7	265.0	261.9
964.0	416	-12.7	-17.7	66	0.99	6	1	263.2	266.0	263.4
939.7	610	-13.6	-17.9	70	1.00	350	2	264.2	267.1	264.4
925.0	730	-14.1	-18.0	72	1.01	350	3	264.9	267.8	265.1
909.0	862	-14.5	-18.3	73	1.00	350	4	265.8	268.7	266.0
902.8	914	-14.1	-19.1	66	0.94	350	5	266.8	269.5	266.9
898.0	955	-13.7	-19.7	61	0.90	351	5	267.6	270.2	267.7
886.0	1058	-9.3	-16.3	57	1.21	352	5	273.1	276.7	273.3
867.7	1219	-9.9	-16.9	57	1.18	355	5	274.1	277.6	274.3
850.0	1378	-10.5	-17.5	56	1.14	320	4	275.1	278.5	275.3

Figure 27. RAOB data from 00Z on 04 Dec 2005. From UWSP, 2007.

From 925mb-850mb, the winds varied a lot during the 48-hour period examined, starting off out of the north and light (8kts), before veering to the east and lightening further (3-5 kts). The winds then backed to northerly again by 12Z on 4 Dec, but by 00Z on the 5 Dec, began to increase drastically (15-20 kts) and come out of the east. This coincided with a massive increase in water content, going from 1.1 g/kg to nearly 1.9 g/kg. The significant events in the vertical profile to the fog formation appeared between 00Z-12Z on 4 Dec, when the temperature increased from -18°C to -15°C (Fig. 28), allowing for a stronger inversion to set up, and creating a second stable layer above the near surface inversion.

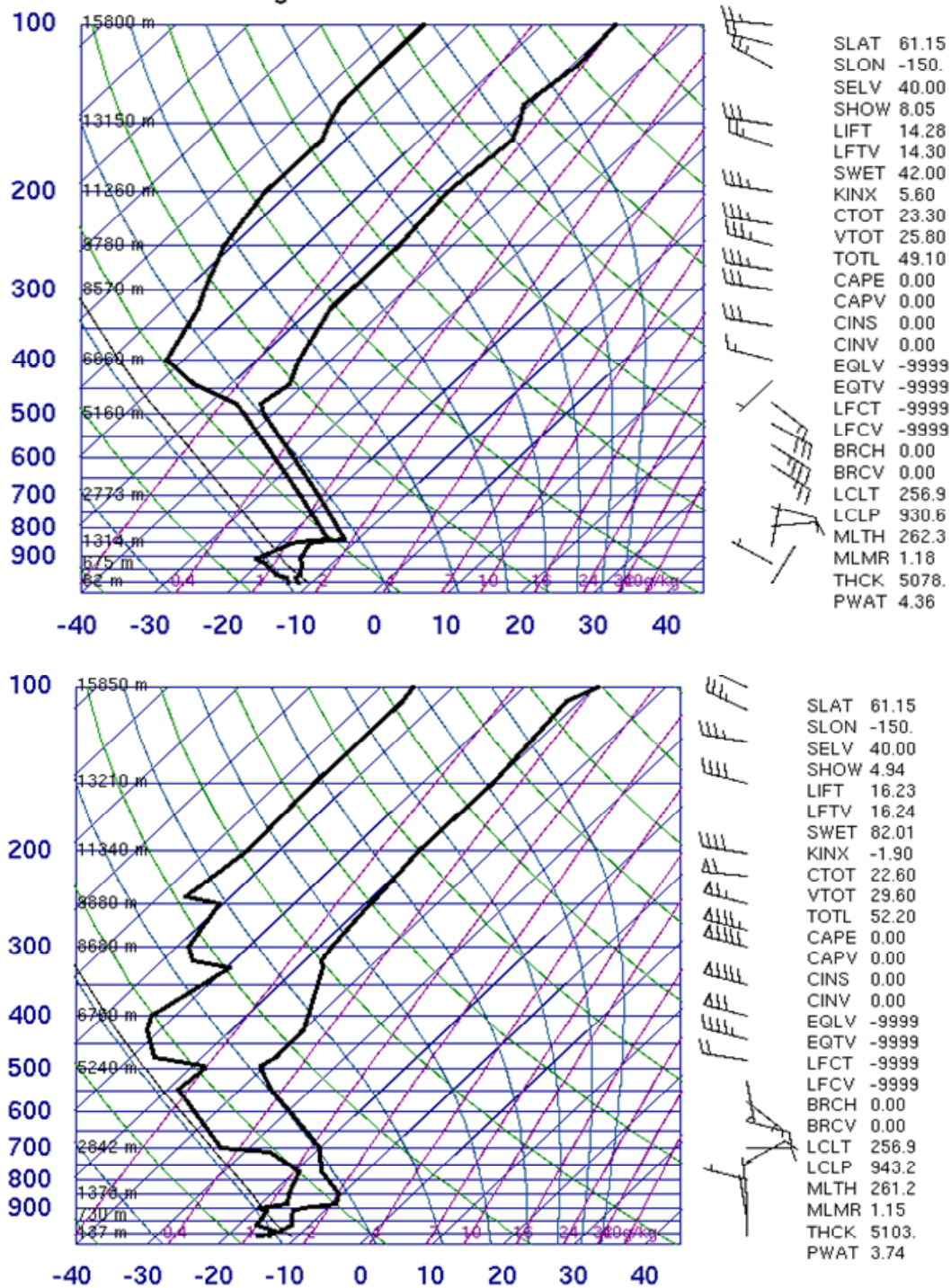


Figure 28. Upper-air sounding from PANC launched at 00Z (top) and 12Z (bottom) on 4 Dec 2005. From UWSP, 2007.

4. Case Summary

This event began with a synoptic low pressure system in place just to the east of the base, which initially was producing winds from the northeast. As time progressed, a strong Siberian High started towards the base, impacting the wind flow at the surface, and making it more northerly. Relatively dry conditions on 3 Dec allowed for strong radiational cooling to occur overnight, which appeared to help condense the boundary layer. Moisture entered the region in the low levels (from surface-975mb) at a time that correlated with high tide. The fog lasted for nearly 16 hours before giving way to a warmer, moister air mass.

The stratus in this event appeared to already be at the surface at the start of the event, and did not look as though it needed to be mixed from above in this case. The visible satellite image from just after the end of the fog event showed a pool of fog against the Chugach Range, but is believed to have initially formed over the entire region. The indications in the low levels were that there was enough moisture content at the surface to get fog from radiational cooling alone. After sunrise, however, differential heating occurred, and the fog receded to the cooler areas (i.e., the base of the mountains). The fog redeveloped after sunset, until winds increased enough to produce eddy-kinetic turbulent mixing in the boundary layer.

D. CASE 3 (13-14 JAN 2006)

The fog event that occurred on 13-14 Jan started under a similar synoptic pattern to the first case. A low pressure center was approximately 400 NM southeast of Elmendorf AFB, with an inverted trough stretching northwestward towards the base. An arctic high was in Canada, with the main ridge axis extending westward into the Alaskan Interior. A strong low pressure system was well west of Alaska, but was moving towards the base, and was impacting the pressure gradient near the base. A stratus deck formed at 05Z on 13 Jan, just 2 hours after high tide, and stayed around for the remainder of the day. Fog finally formed at 1127Z on 13 Jan, but only lasted for 6 hours. On 14 Jan, the fog

returned at 0230Z, and lasted for most of the rest of the day. The temperatures were as high as -6°C on 12 Jan, but never got above -11°C for the rest of the period, as the result of a strong cP air mass settling into the region. The winds, like in the previous cases, were very light for the entire period, with a mainly northeasterly-easterly component.

1. Synoptic Overview

At this point, an obvious synoptic trend had appeared in all of the events. The sea-level pressure analysis of this case, like the 2 previous, showed a weak low pressure system in the Gulf of Alaska, with a strong arctic high sitting along the AK/CAN border at 00Z on 13 Jan (see Fig. 29). The interaction between the two pressure systems (and an Aleutian Low) was creating a pressure gradient force that was inducing a northerly wind flow into the forecast region. When compared to case 1 specifically, the pressure pattern was very similar.

By 14 Jan, the low pressure area to the southeast moved slightly north, and weakened (as did the associated inverted trough), while the Aleutian Low moved towards the forecast area (see Fig. 30). While the gradient was not as strong near the base by this time period, it was still producing a northerly component of wind just above the surface, which was helping to cool temperatures in the Anchorage Peninsula. This weaker gradient was favorable to fog maintenance, since the inherently weaker winds associated with the gradient would not destroy the fog through mixing.

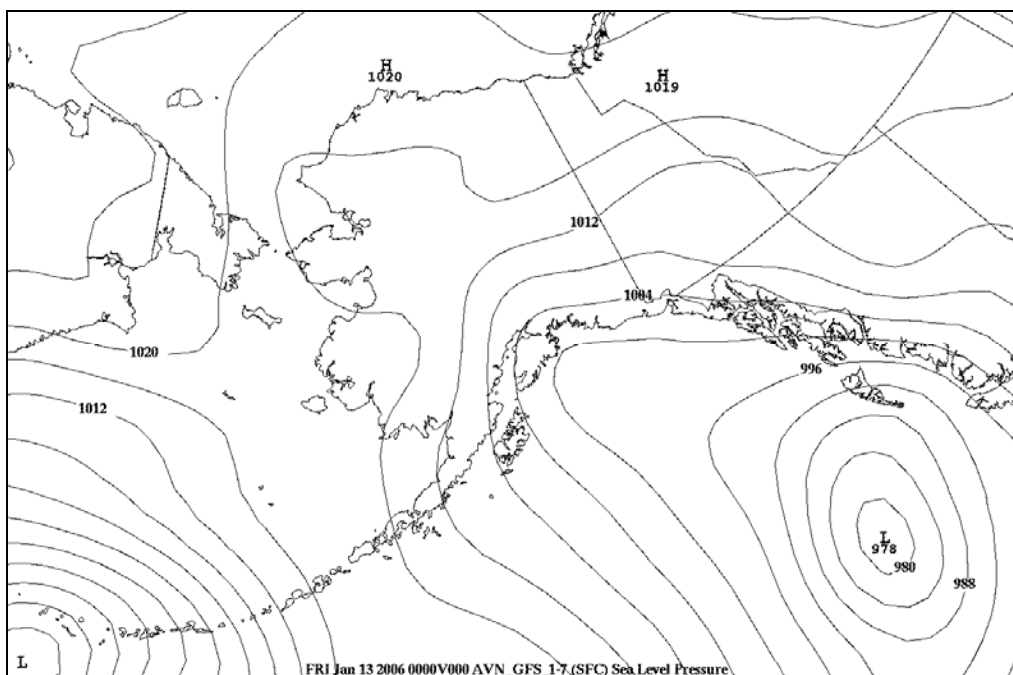


Figure 29. Sea-level pressure analyses for AK on 13 2006 at 00Z. From Plymouth State Weather Center, 2007

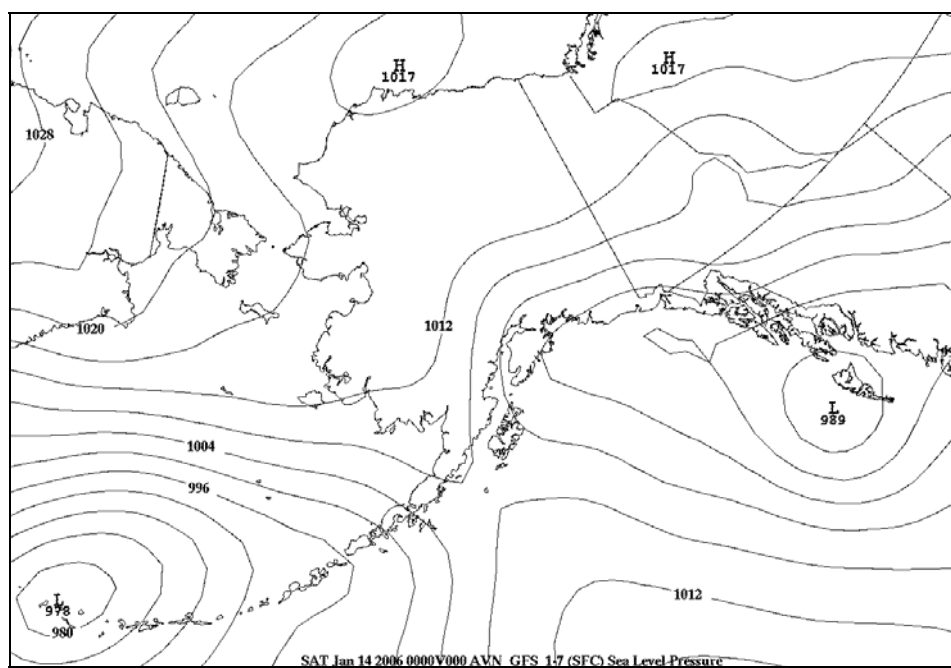


Figure 30. Sea-level pressure analyses for AK on 14 Jan 2006 at 00Z. From Plymouth State Weather Center, 2007

By the end of the fog event on 15 Jan, the pressure gradient had now shifted around to a northeasterly component, as the strong Aleutian low headed south of the forecast area, and forced the smaller, weaker low to the southeast into British Columbia (Fig. 31). A weak low was analyzed just to the southeast of the base, and was likely a reflection of an upper level minor shortwave that was propagating around the major shortwave axis. This low helped to induce a more zonal flow from the southeast, which favored warmer and moister air mass for the region. This air mass and vertical motion from shortwave energy is believed to be responsible for the light snow and slightly warmer temperatures that started late in the day on 15 Jan.

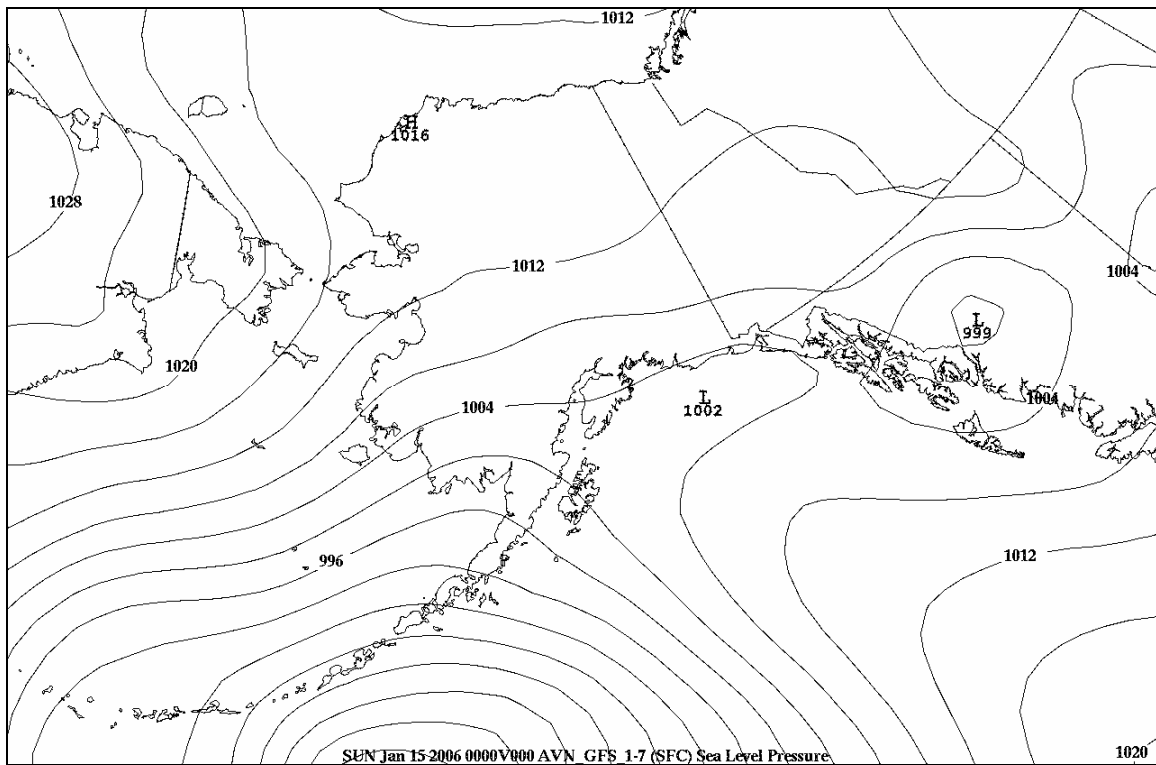


Figure 31. Sea-level pressure analyses for AK on 15 Jan 2006 at 00Z. From NCAR/NCEP, 2007

2. Observational Analysis

Fog formed and lasted for 6 hours the first day of the case (from 13/11Z-13/17Z) and for 13 hours the second day (from 14/2Z-14/15Z). Both of the days had uninterrupted fog restrictions, and it appeared as if the second day was a

longer event because of the persistence of conditions. But, after a closer examination, something appeared to be a bit unusual. As always, there was significant mid-level cloud cover for the duration of the observation period. A stratus deck at 100ft appeared at 05Z on the 14 Jan, nearly 6 hours before the fog developed. This stratus deck was similar to what had been seen in previous cases. But this time around, there was a much greater lag between the presence of this deck and the formation of fog.

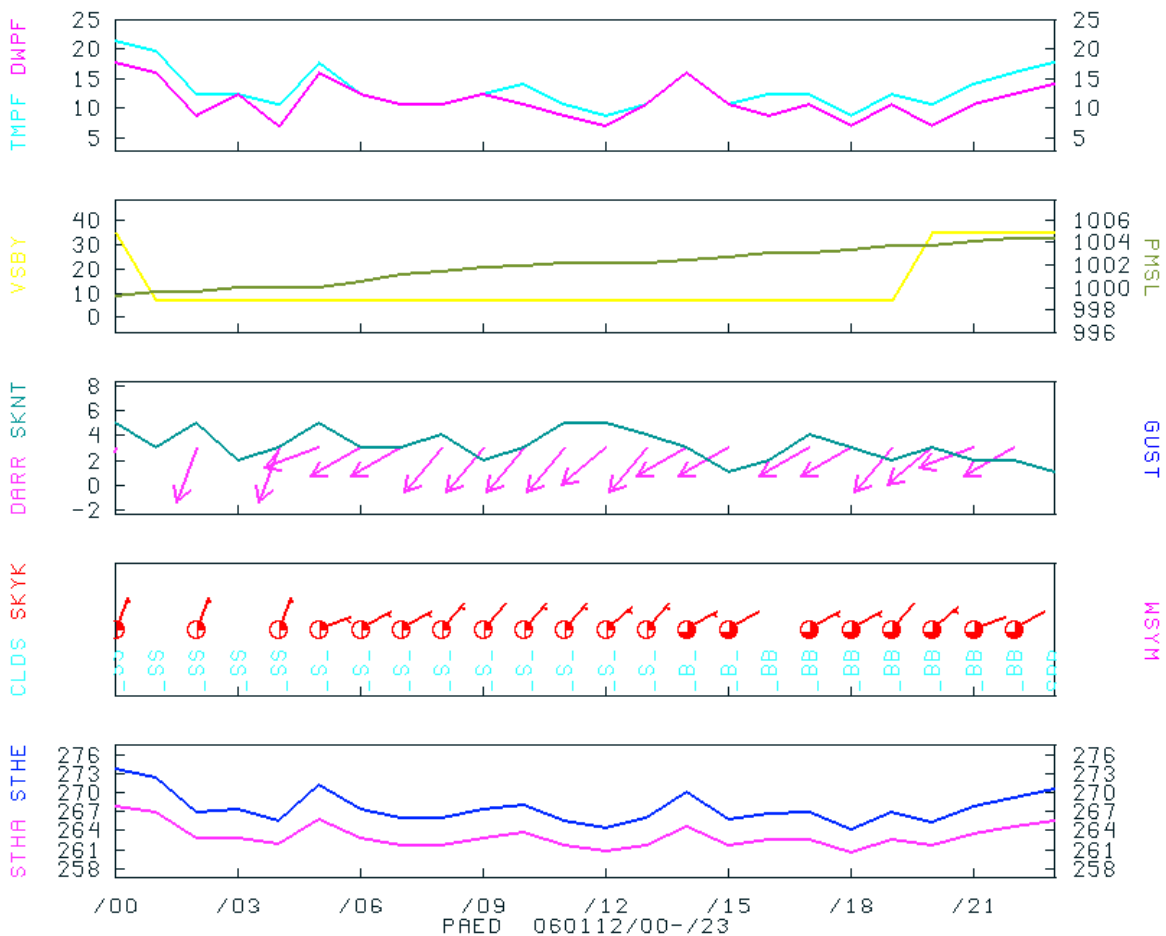


Figure 32. Meteogram for PAED on 12 Jan 06. From NCEP/NCAR, 2007.

On 12 Jan, no significant weather impacted the base (Fig. 32). The temperature, for the most part, followed the expected diurnal variation, and had a range from -8°C to -13°C or just slightly below the monthly mean for January. Throughout the day, a mid and upper-level cloud deck remained in place at

10000 ft and 25000 ft respectively. The cloud cover did increase in coverage throughout the day, going from few in the morning to broken by evening. Winds remained light and from the northeast-east for the duration of the day.

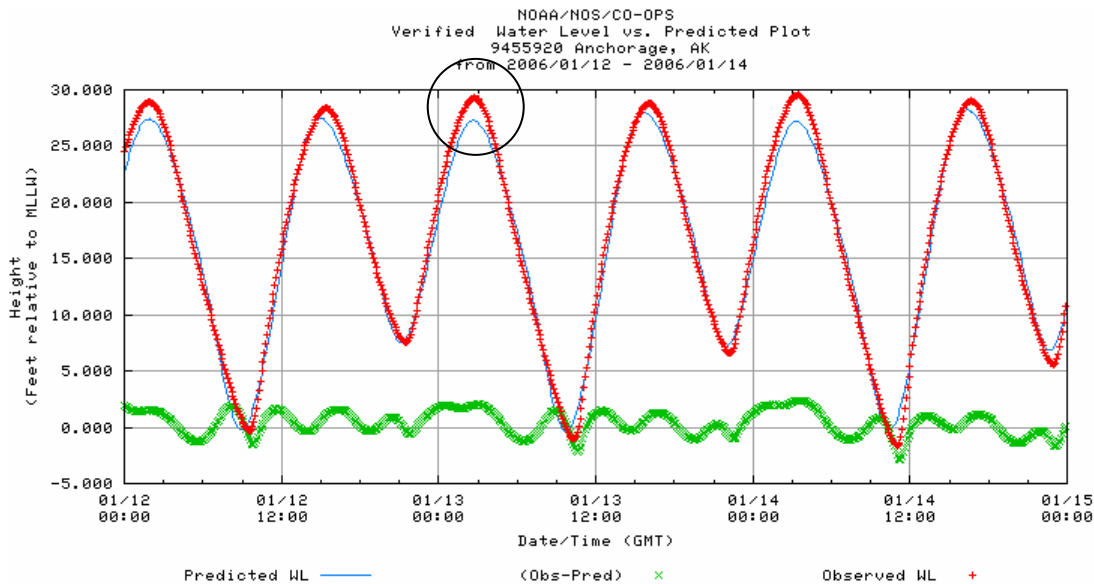


Figure 33. NOAA plot of water level vs. predicted water level for Anchorage, AK (Cook Inlet) for the period from 12-14 Jan 2006. From NOAA, 2007.

On Jan 13, conditions began to deteriorate, starting first with the reported stratus deck at 100 ft at 0508Z, just two hours after the high water level (see Fig. 33). The cloud cover then seemed to stream over the base in a staggered fashion, going from few to broken, back to few, and then finally going overcast, with freezing fog occurring simultaneously. A closer look did not indicate any significant changes in the observation at the time that the stratus appeared (indicated by the line on the left in Fig. 34). The temperature was erratic during this time as was the dew point temperature. The winds did not change, and the visibility stayed at 7SM. Even at the time when the fog did finally form (indicated by the line on the right in Fig. 35), there did not appear to be any notable factors to correlate with the fog. While the temperature and dew point temperature both rose between the times that the stratus was observed and the beginning of the

fog, there was likely some background change from radiational cooling, which prevented an even greater rise in temperature and dew point temperature, at least based on the trend from the previous cases. Similar to the first case, it is believed that the fog formed around the base, and due to weak forcing from drainage winds along the Chugach Range, was able to “advection” towards the base. Fog was lying all around the base from the west-north-east (Fig. 35). There was likely some background noise from radiational cooling, which prevented an even greater rise in temperature and dew point temperature, at least based on the trend from the previous cases. Similar to the first case, it is believed that the fog formed around the base, and moved over the base during the night.

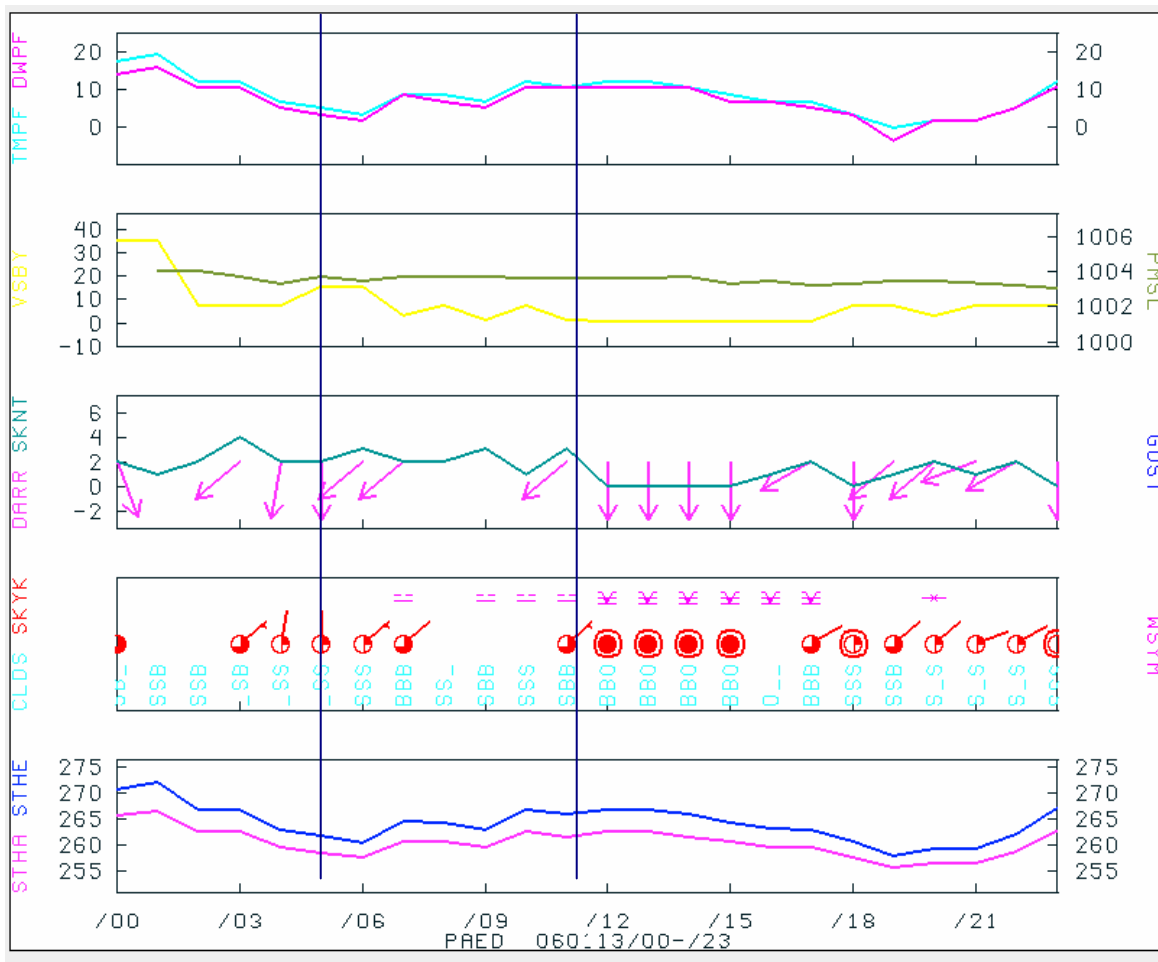


Figure 34. Meteogram for PAED on 13 Jan 06. From NCEP/NCAR, 2007.

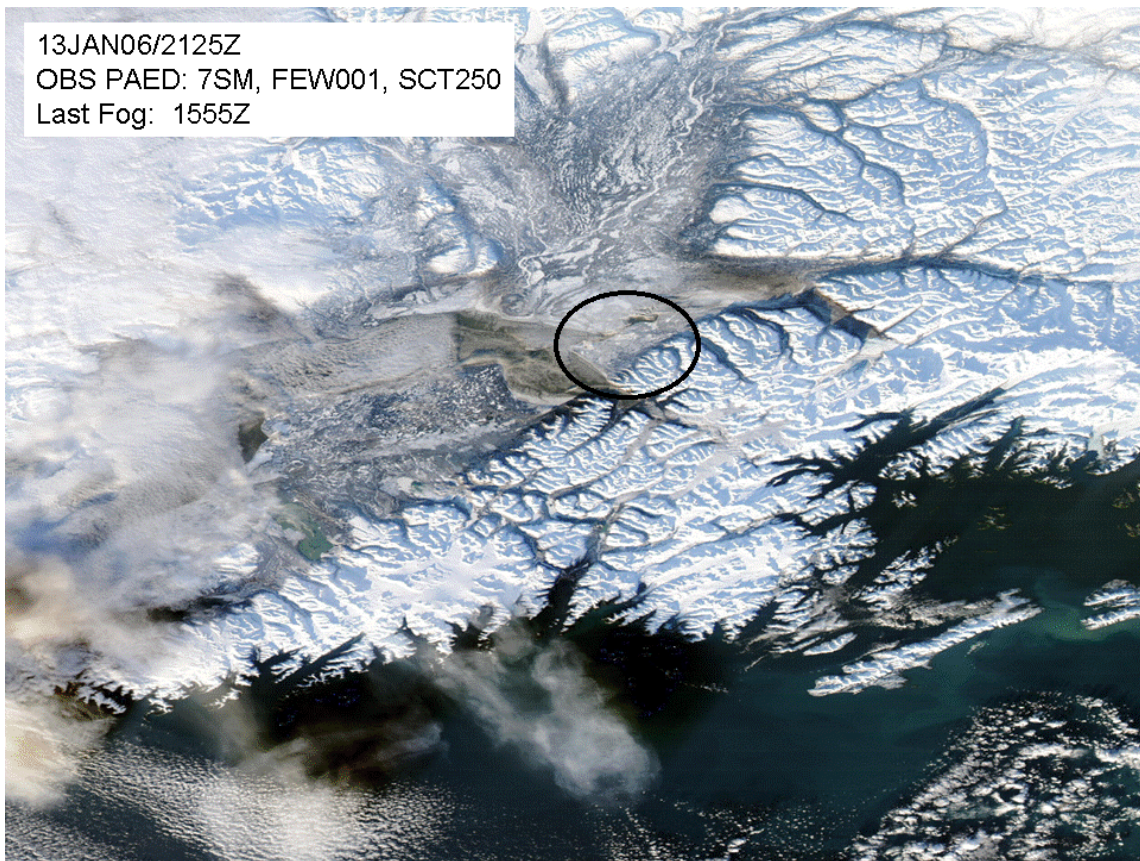


Figure 35. Aqua-Modis 250m High Resolution visible images taken on 13 Jan 2006. From MODIS Rapid Response, 2007.

On UTC 14 Jan, fog developed just after sunset, and remained in place until just after sunrise (although the fog towards the end of the morning was intermingled with light snow). The fog developed without much notice, as the visibility went from 7SM at 01Z to 1/2SM at 0230Z, and a slight change in temperature or dew point temperature occurred (indicated by the line in Fig. 36). Like the previous case, fog was sitting nearby, but to the east this time (see Fig. 37), and when the temperature cooled enough in the Chugach Valley, the fog began to be forced towards the base. This slightly warmer and more moist fog bank was likely responsible for the rise in both temperature and dew point temperature. Coincidental to the fog moving in from the east was a wind shift

from northeasterly to easterly. Easterly winds have been studied at the base, and been shown to cause warming through compression. In this event, however, the fog appeared to be pushed by the drainage flow, which inherently increased the winds when the fog arrived

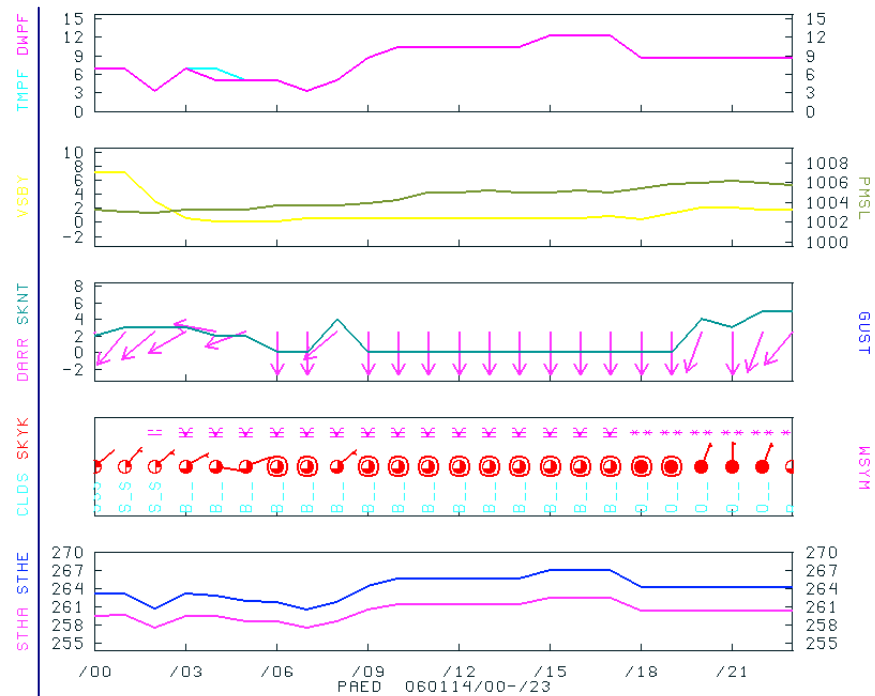


Figure 36. Meteogram for PAED on 14 Jan 06. From NCEP/NCAR, 2007.

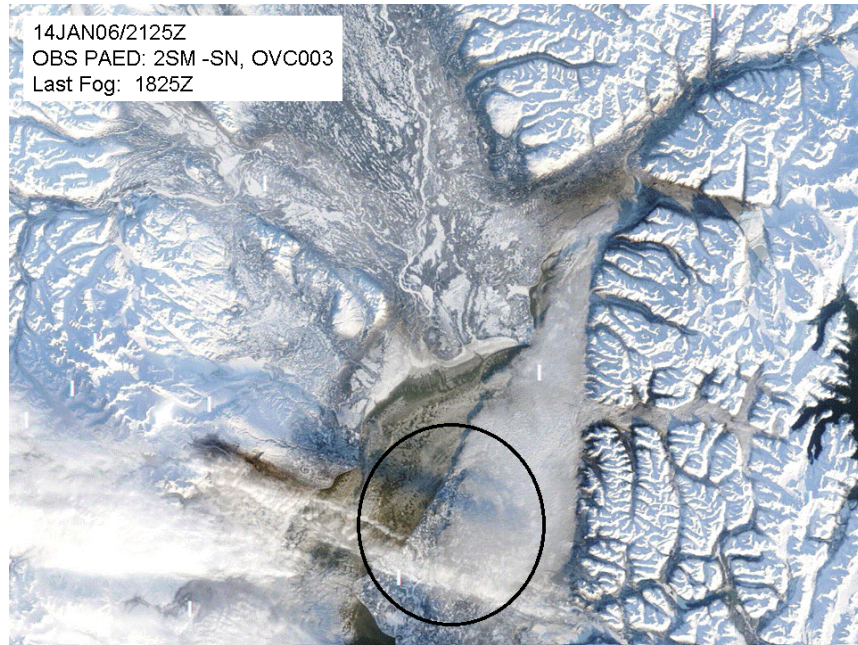


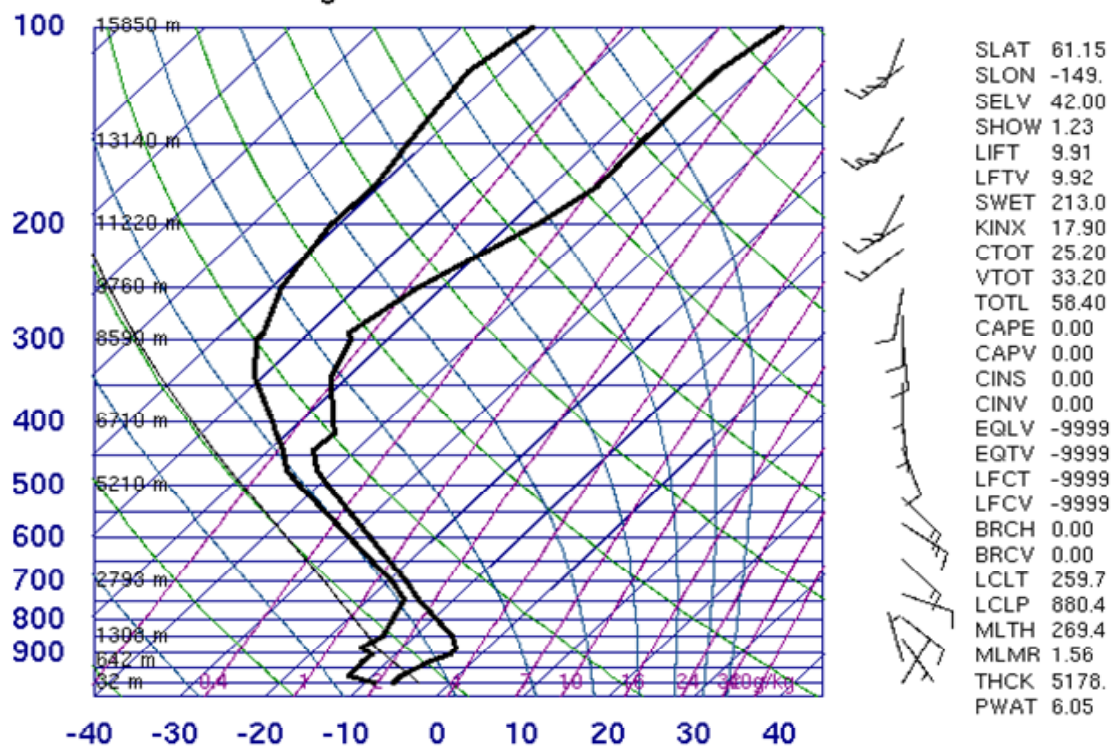
Figure 37. Aqua-Modis 250m High Resolution visible images taken on 14 Jan 2006. From MODIS Rapid Response, 2007.

3. Sounding Analysis

Fortunately during this event, there were staggered 6-hour soundings, which provided much more detail than was available in previous events. The sounding data again revealed the advection of mid-level moisture and light wind speeds out of the northwest-north just above the surface, or from a direction favorable to advect low-level moisture from Knik Arm.

In the sounding taken at 00Z on 13 Jan, there appeared to be a favorable setup for a radiation fog event, if temperatures going into the night could reach approximately -10°C , as the dew point temperature was at approximately -10°C (Fog. 38). There was also a strong dry layer just above the surface. Observations at both PANC (where the sounding is taken) and PAED were reporting a very widely scattered deck.

70273 PANC Anchorage



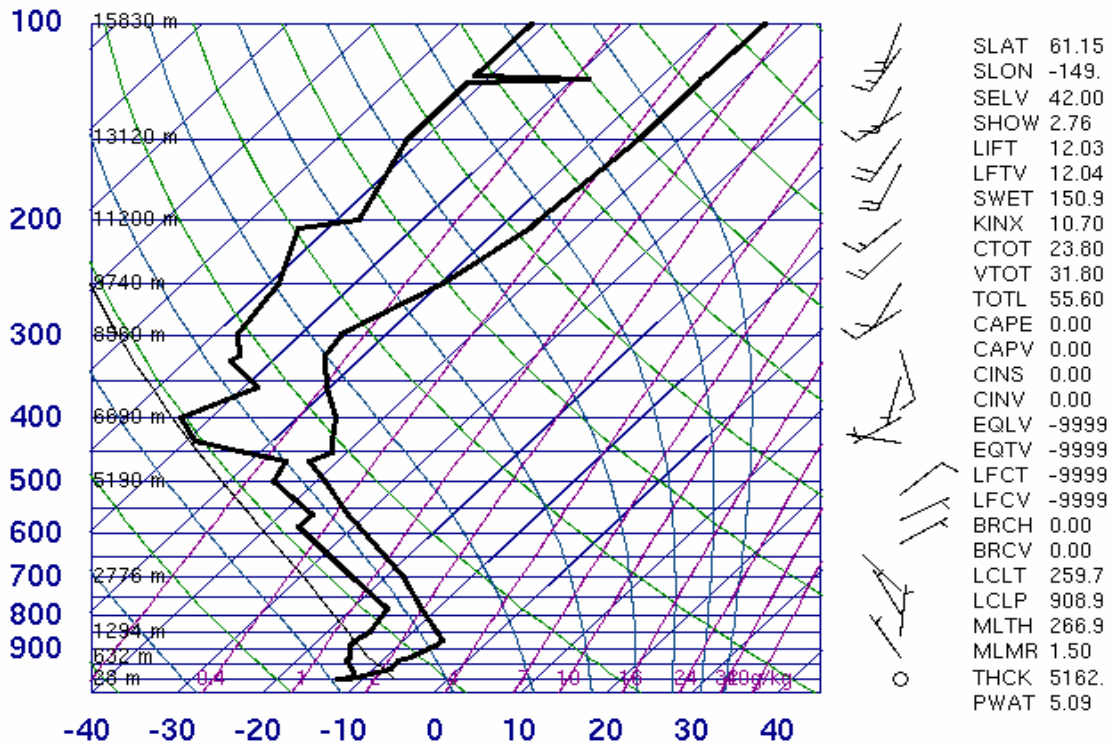
00Z 13 Jan 2006

University of Wyoming

Figure 38. Upper-air sounding from PANC launched at 00Z 13 Jan 2006. From UWSP, 2007.

By 12Z on 13 Jan, the sounding showed a shallow saturated layer near the surface, with drying above 975mb (Fig. 39). This profile appeared to be a case of radiational cooling at the surface, leading to radiation fog. There was a general cooling and drying of the boundary layer, except at 965mb, where the temperature fell, but the dew point rose (indicating an influx of moisture). This level (approx. 300m) did not appear to be saturated enough to produce a cloud deck, but did suggest that moisture advection was occurring just above the surface, and may have been relevant to the formation of the fog. reporting a very widely scattered stratus deck. While the sounding did not depict this, it is likely that the observations were reporting stratus that was not on station, but rather to the east of the observations sites.

70273 PANC Anchorage



12Z 13 Jan 2006

University of Wyoming

Figure 39. Upper-air sounding from PANC launched at 12Z 13 Jan 2006. From UWSP, 2007.

The 00Z sounding from PANC on 13 Jan showed that the inversion from the morning of 13 Jan was so strong that it did not completely break on Jan 13 during the day, which meant that no mixing was able to occur (Fig. 40). This coincided with an unusual occurrence, at least during this study, which was that PANC was reporting freezing fog, while PAED was not. PAED did begin reporting fog at 0229Z with northeasterly winds. The fog and stratus just before this time appeared to be impacting the southwestern portion of the Anchorage Peninsula, as well as the locations east of the base against the mountains, but not the base. This was verified by satellite (Fig. 35), which indicated that fog was lying around the base on 3 sides (west-north-east), but was not quite on station.

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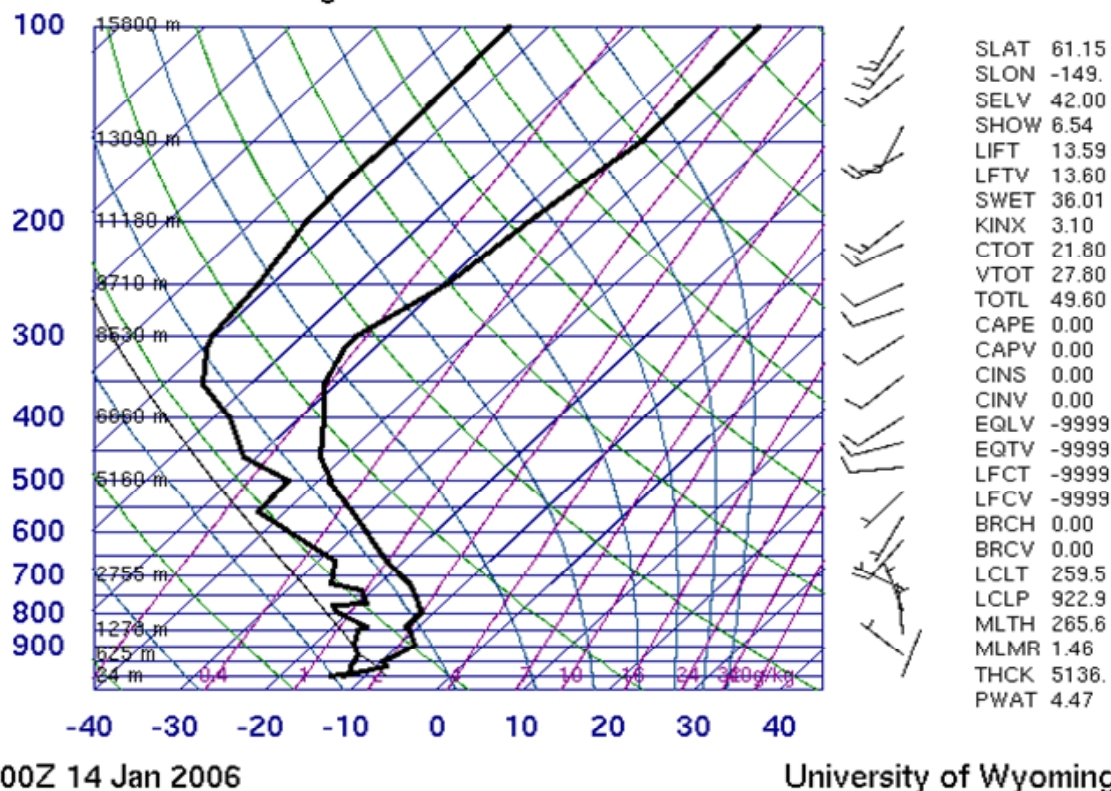
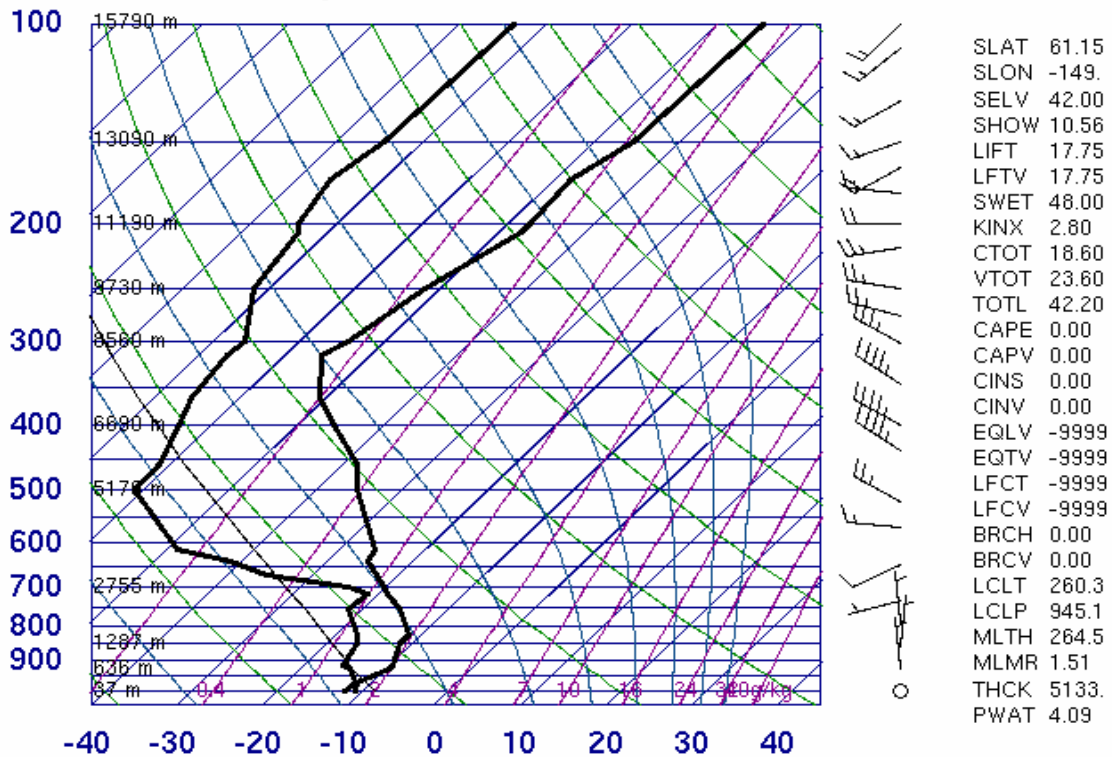


Figure 40. Upper-air sounding from PANC launched at 00Z 14 Jan 2006. From UWSP, 2007.

As time went on through Jan 14, the sounding indicated a very moist and stable boundary layer just above the surface (Fig. 41), with a very shallow surface based unstable layer. Freezing fog was reported at PANC at this time, with an overcast deck at 100ft. This cold pocket just above the surface was believed to be producing just enough instability to promote weak mixing, which helped to keep the surface saturated through vertical moisture flux from above.

70273 PANC Anchorage



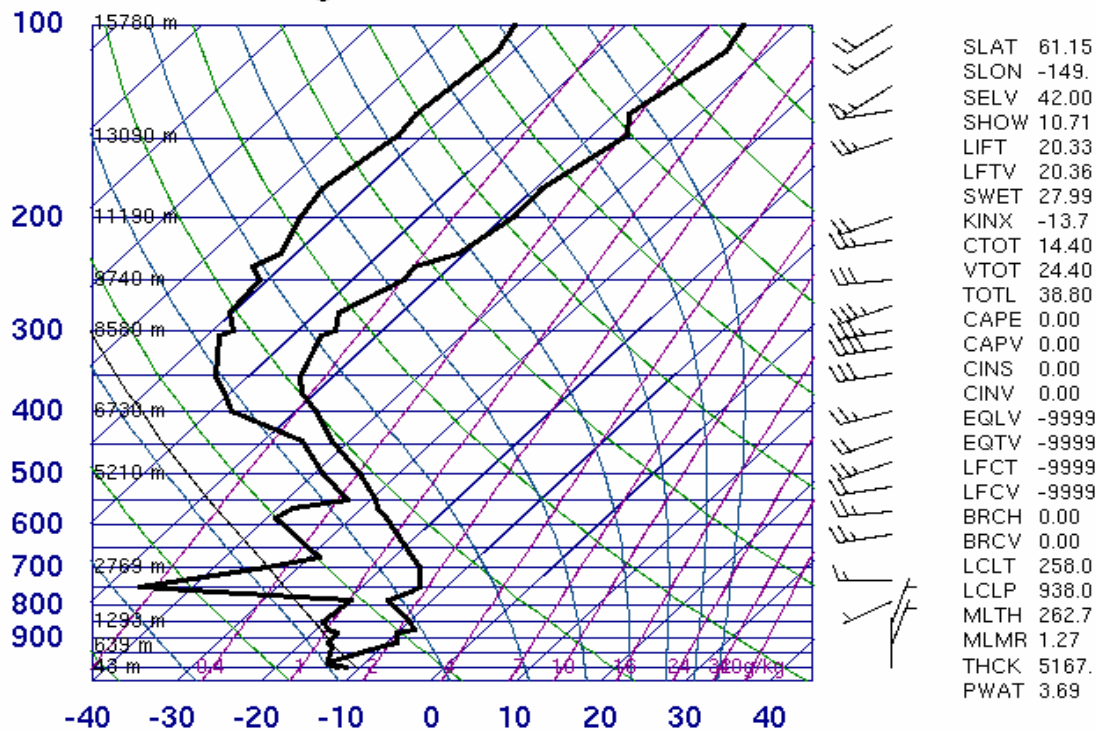
12Z 14 Jan 2006

University of Wyoming

Figure 41. Upper-air sounding from PANC launched at 12Z 14 Jan 2006. From UWSP, 2007.

The unstable layer continued into 00Z on 15 Jan (Fig. 42), and at this time, was apparently significant enough to be producing light snow. The visibility increased, and presumably, so did the vertical motion. Winds at this time were from the northeast, and the air mass was undergoing another change, towards a more mP air mass. The fog appeared to mix out, and turn into a snow producing stratus deck, mainly to the east of PAED.

70273 PANC Anchorage



00Z 15 Jan 2006

University of Wyoming

Figure 42. Upper-air sounding from PANC launched at 00Z 15 Jan 2006. From UWSP, 2007.

4. Case Summary

Case 3 was a two-day event that began on 13 Jan. The overall synoptic pattern consisted of a low pressure system to the southeast interacting with a ridge in the Alaskan Interior, and a strong trough along the Aleutian Chain. This induced a northerly pressure gradient wind flow near the surface. This enabled a cP air mass to drain into the Anchorage Peninsula from the Alaskan Plateau, dropping temperatures some 10°C below monthly means. The first day of fog was short-lived, only lasting for 6 hours, before lifting, although a stratus deck remained in place for the entire day. On 14 Jan, fog reformed over the base at 0229Z, and lasted for nearly 15 hours. This freezing fog persisted in the region, an eventually lifted into a snow-producing stratus deck by 15 Jan.

This event appeared to form as the result of stratus advecting into the region just above the surface, and correlated well with high tide again. With the aid of radiational cooling, fog formed in the vicinity and seemed to drain towards the base. Diurnal effects presumably allowed for the fog to “burn-off” over the base, but not in other nearby areas (as was indicated in the satellite images). When the fog re-entered on 14 Jan, it coincided well with sunset, and was likely driven initially by radiational cooling. However, the sustainment of this event appeared to come through vertical mixing with the stratus deck, since soundings indicated that there was a shallow layer of instability at the surface throughout the day. This instability likely became strong enough by 15 Jan to cause snow to develop.

E. CASE 4 (18 JAN 06)

This event lasted for only 12 hours, and was not as intense as the previous events. However, it was a mission limiting fog event nonetheless. The genesis of this event began with a low pressure center to the southeast of the base that had an inverted trough extending towards the base. This trough interacted with a ridge to the north, and another trough to the west. As time progressed towards the day of fog, the pressure gradient over the base went from easterly to northerly, favoring winds from the much cooler cP air mass sitting north of the base on the other side of the Alaskan Range. A stratus deck appeared at 22Z on 17 Jan, about 4 hours after high tide, and persisted for the next 2-days, although it began to lift by 22Z on 18 Jan, and coincidentally, the fog diminished. Fog formed nearly 8 hours after the stratus was reported, which was longer than had been seen in the previous cases.

1. Synoptic Overview

Beginning with a look at the pressure pattern on 17 Jan (Fig. 43), a weak low pressure system was setting up in the Gulf of Alaska, and was retrograding back towards Elmendorf AFB. At the same time, a fairly strong high pressure

center had made its way to the AK/CAN border, with a ridge axis stretching westward into the AK interior. There was also a high pressure center in the Bering Sea, which when combined with the other pressure features, was creating a relatively tight gradient over the base. At this point, however, the gradient was from the east, and was not favorable to produce the necessary cold air advection at the surface, as was seen in the pervious events.

The following day, the pressure pattern was more favorable for a fog event (Fig. 44), as the pressure gradient was now aligned in a north-south orientation, which allowed for cold air to drain into the Anchorage Peninsula from on the other side of the Alaskan Range, where temperatures were nearly 15°C colder. The reason for this change was that a low had developed along the inverted trough, and was very close to the base on the east. This low likely developed as the result of shortwave energy rotating around the main low pressure center to the southeast, which produced enough positive vorticity advection to reflect a low pressure center at the surface.

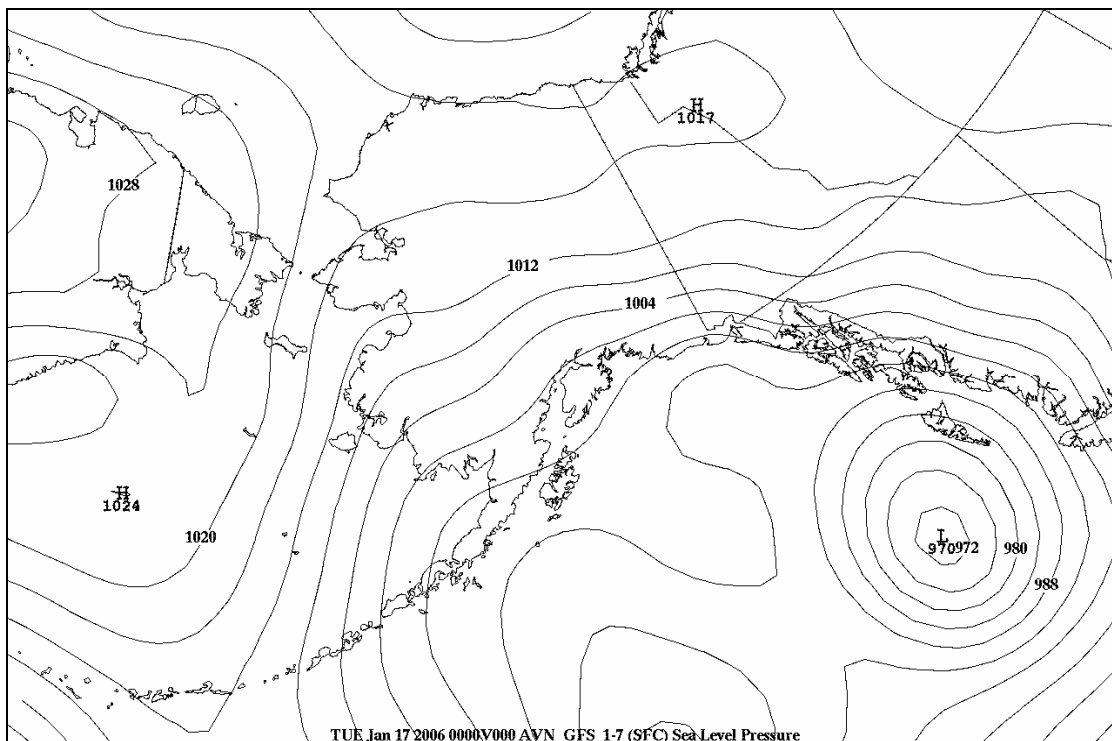


Figure 43. Sea-level pressure analyses for AK on 17 Jan 2006 at 00Z. From NCAR/NCEP, 2007

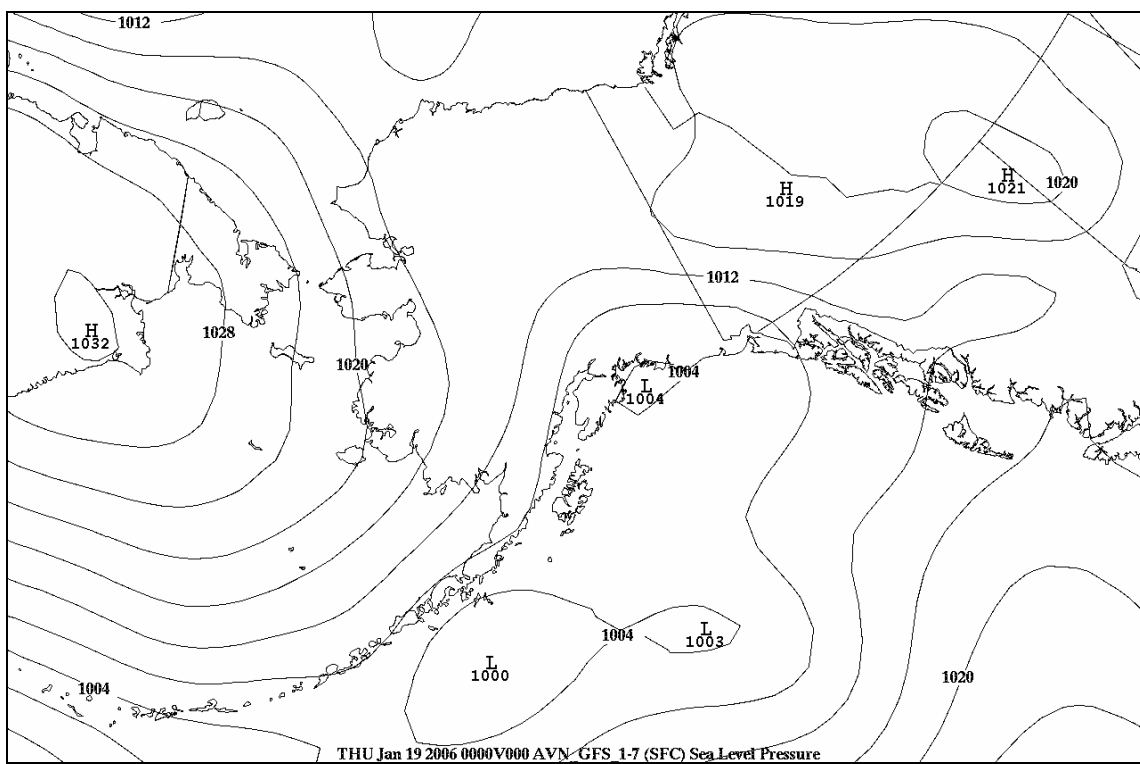
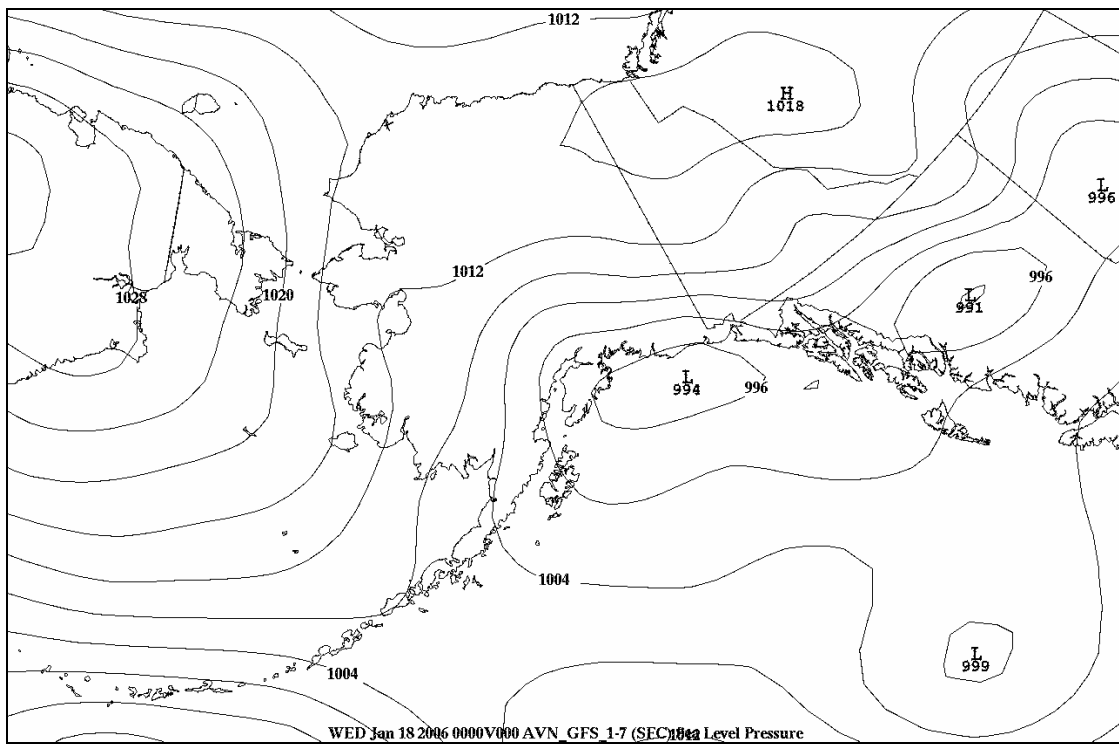


Figure 44. Sea-level pressure analyses for AK at 00Z on 18 Jan (top) and 00Z on 19 Jan (bottom) 2006. From NCAR/NCEP, 2007

By 19 Jan, the low was nearly on top of the base (Fig. 44), and was now producing enough vertical motion to lift the fog, and produce light snow in the region. Also, in response the proximity of the low, the pressure gradient became a bit stronger, which inherently increased wind speeds at and just above the surface. At this point, the fog had ended, and a new air mass (mP) was about to enter the region.

2. Observational Analysis

On Jan 17, the observations indicated that there was minimal cloud cover, and cool temperatures (Fig. 45). The winds were calm or light and generally from the east, and the cP air mass from the north appeared to have moved into the region.. The mid and upper-level cloud cover fluctuated throughout the day in both height and coverage, but at 22Z, a stratus deck appeared at 100 ft, which was only 4 hours after high tide (Fig. 46). At the end of the day, winds remained calm based on observations at PAED. PANC reported winds from the east-southeast during the same time period, but light. By 18 Jan, the first observation from PAED with appreciable wind was the 05Z observation (Fig. 47). However, there were a few missing observations between 00Z-04Z on 18 Jan. The wind was likely blowing during this “blind” period, albeit lightly, based on observations from PANC. The winds at 05Z fluctuated from 040-080, and never got above 2kts. The wind did, however, undergo a fairly large shift from 050-080 at the time that the fog was first observed (06Z). At the same time the wind shifted, the temperature rose by 4°C (Fig. 47). The dew point also rose 4°C, indicating that a new air mass had moved over the base. The cause of this temperature and dew point change was likely a direct impact of the fog, which probably had slightly warmer and obviously moister characteristics. The fog is believed to have “drained” again towards the base from the Chugach Range, as result of cold drainage winds from the valleys. And based on the sudden wind shift at the time the fog formed, it appeared as if the fog originated from the east of the base, along the mountains. The fog lasted for approximately 15 hours, although the

heaviest fog was only in place for about half of the event. The visibility changed frequently during this event, as did the temperature and dew point temperature.

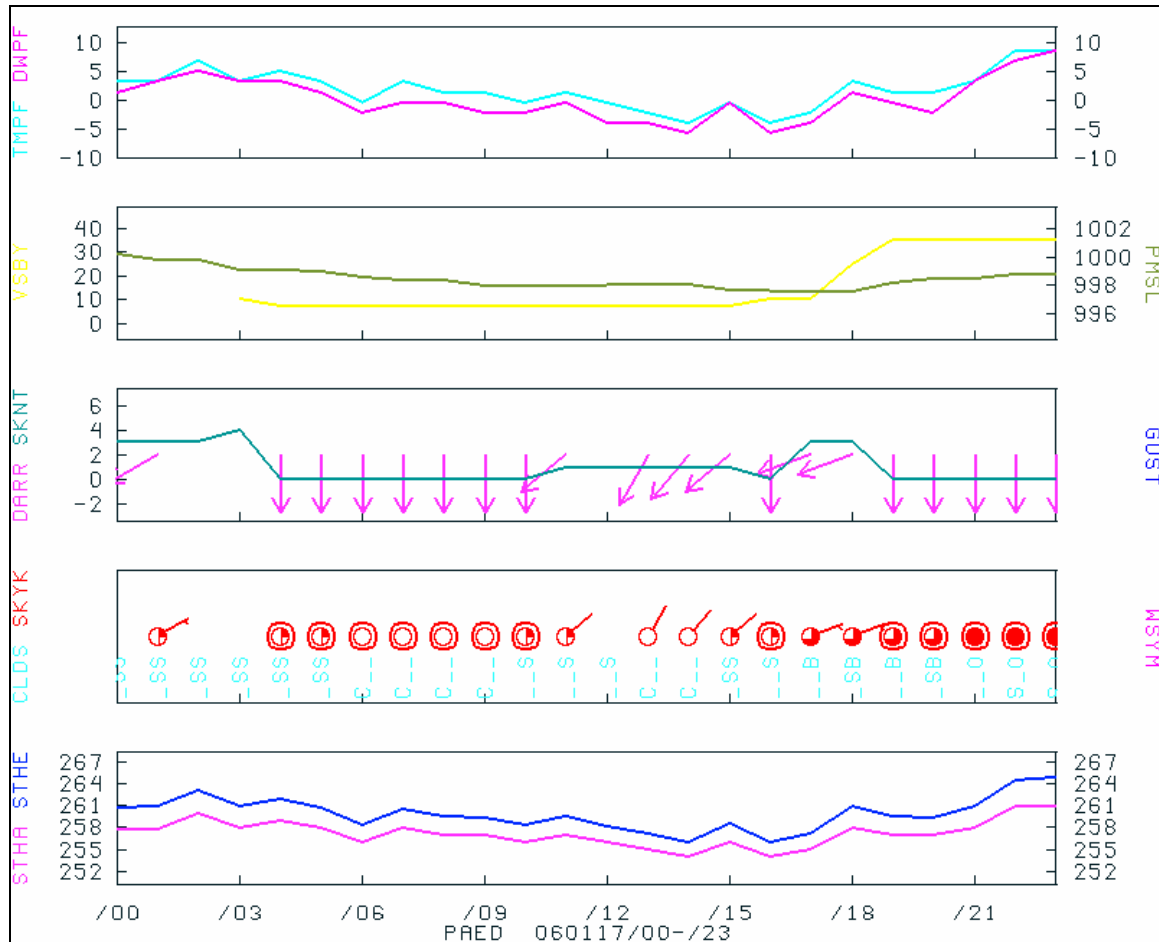


Figure 45. Meteogram for PAED on 17 Jan 06. From NCEP/NCAR, 2007.

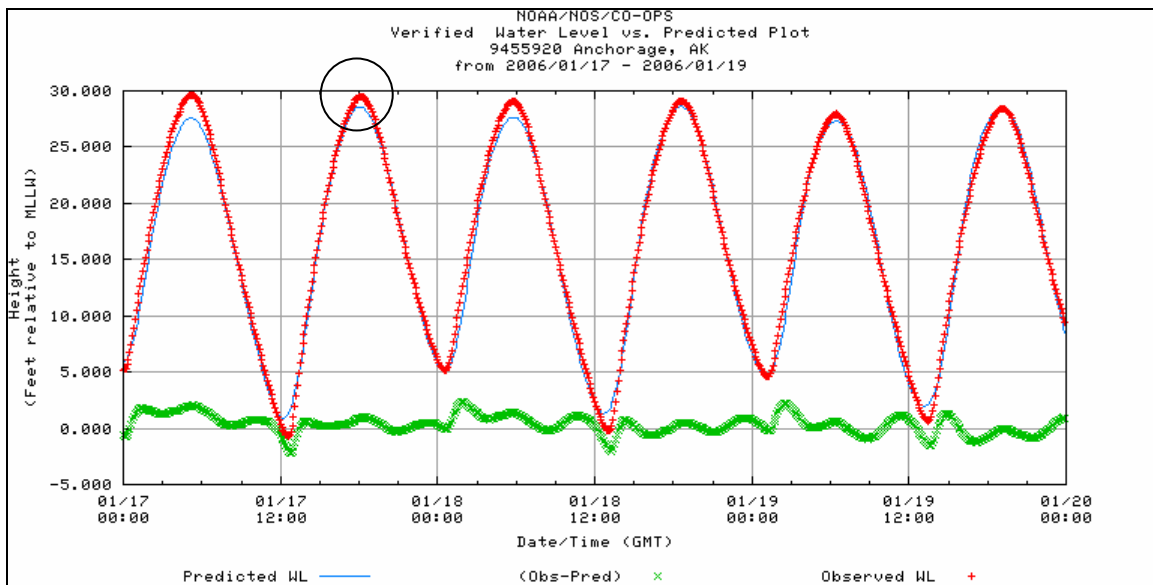


Figure 46. NOAA plot of water level vs. predicted water level for Anchorage, AK (Cook Inlet) for the period from 17-20 Jan 2006. From NOAA, 2007.

Although upstream observations (those to the east) did not indicate the amount of cloud cover, the temperature and dew point temperature warmed approximately 2 hours before they did at PAED. PANC also reported fog on 18 Jan, but it was not observed until 2 hours after it was observed at PAED. This was also supportive of the conclusion that the fog formed to the east of the base, and advected over the base, likely due to cold drainage winds near the Chugach Range, as in the previous cases. A satellite image showed that at 2250Z on 18 Jan (almost 4 hours after the end of fog at the base), a stratus deck was bumped up against the mountains to the southeast of the base (Fig. 48). This led to the conclusion that the fog drifted over the base, and then after sunrise, an “urban heating” effect took place, that warmed the base and the city, and helped mix out the fog over those locations. The temperatures at these locations rose approximately 4°C, more than that of the other surrounding stations.

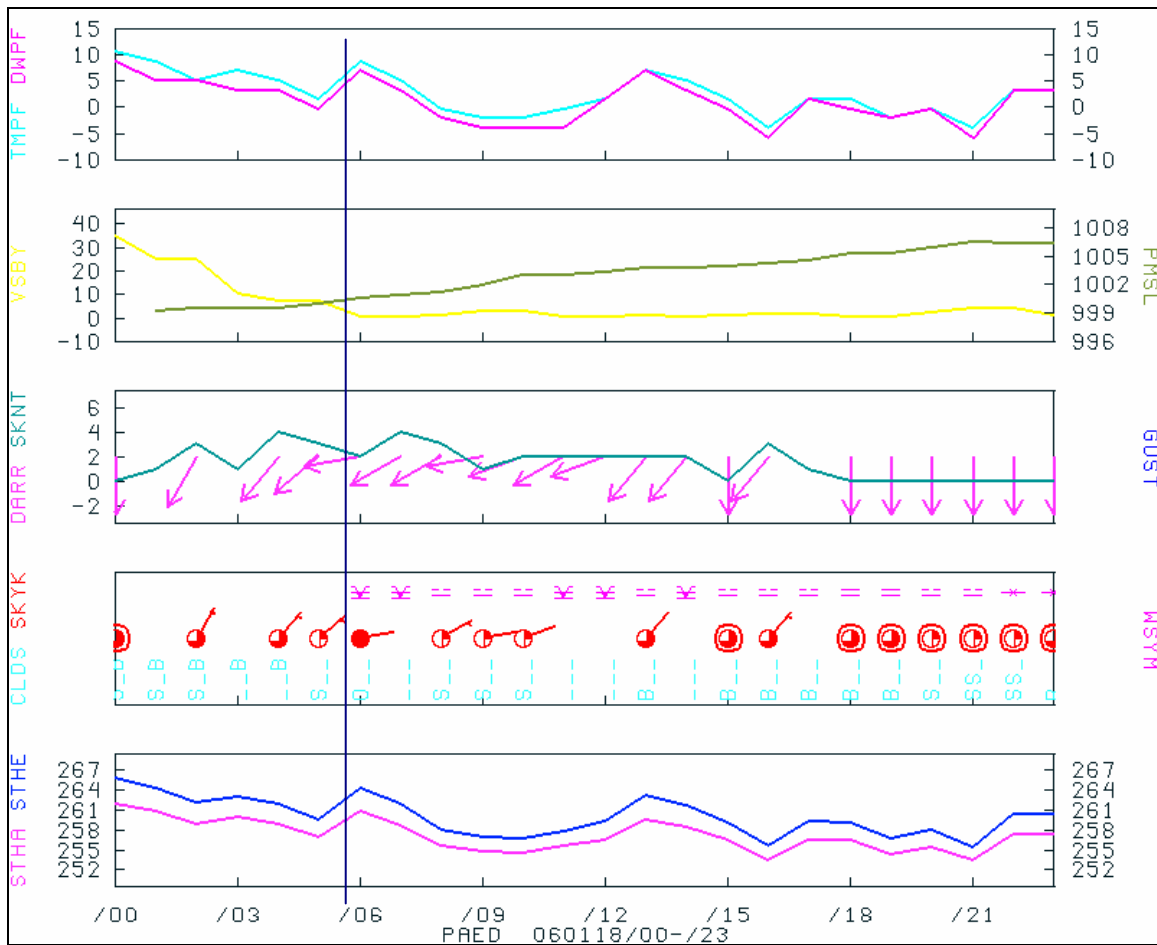


Figure 47. Meteogram for PAED on 18 Jan 06. From NCEP/NCAR, 2007.

On 19 Jan, no fog was reported, and light snow began to fall during the mid-morning (Fig 49). The stratus deck that had hovered at 100 ft had lifted, first to 200 ft, and then to 400 ft after snow began to fall. It appeared at this point that the low center was close enough to force vertical ascent, and helped to mix the boundary layer.

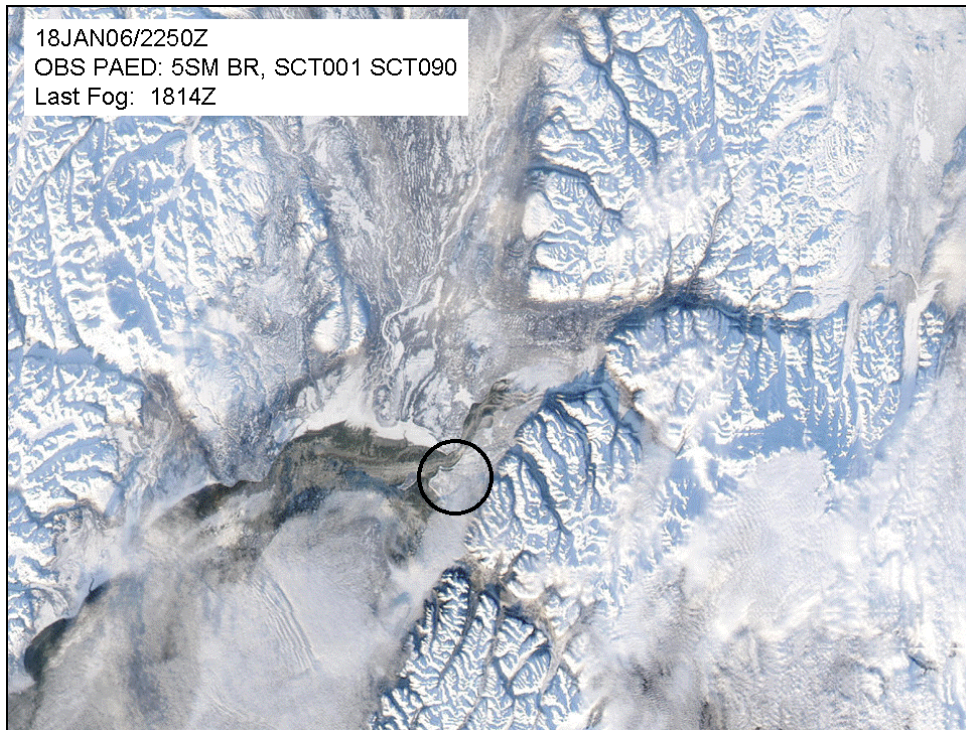


Figure 48. Aqua-Modis 250m High Resolution visible images taken on 18 Jan 2006. From MODIS Rapid Response, 2007.

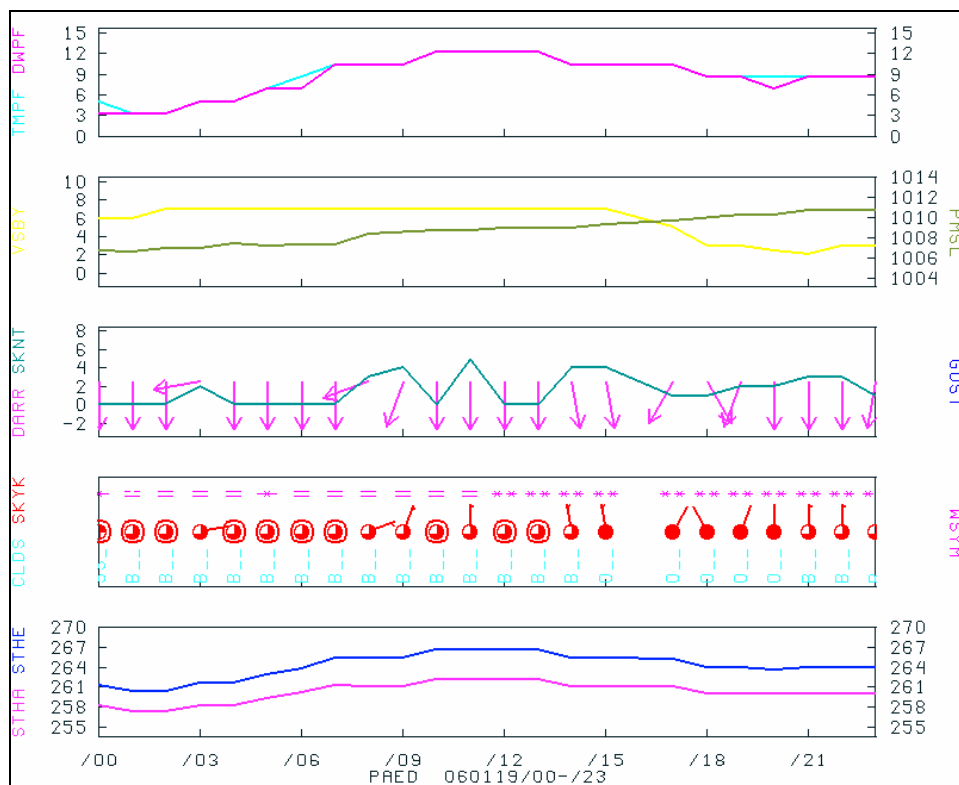


Figure 49. Meteorogram for PAED on 19 Jan 06. From NCEP/NCAR, 2007.

3. Sounding Analysis

A close look at the soundings for this event highlighted the genesis of the boundary layer from a moisture advection perspective. The upper-air data provide credibility to the hypothesis that this event was started by boundary layer moisture advection, and supported by cold drainage flow that took place at the base of the Chugach Range. This case was similar to case 3, especially in terms of the sounding profiles, and the boundary layer characteristics.

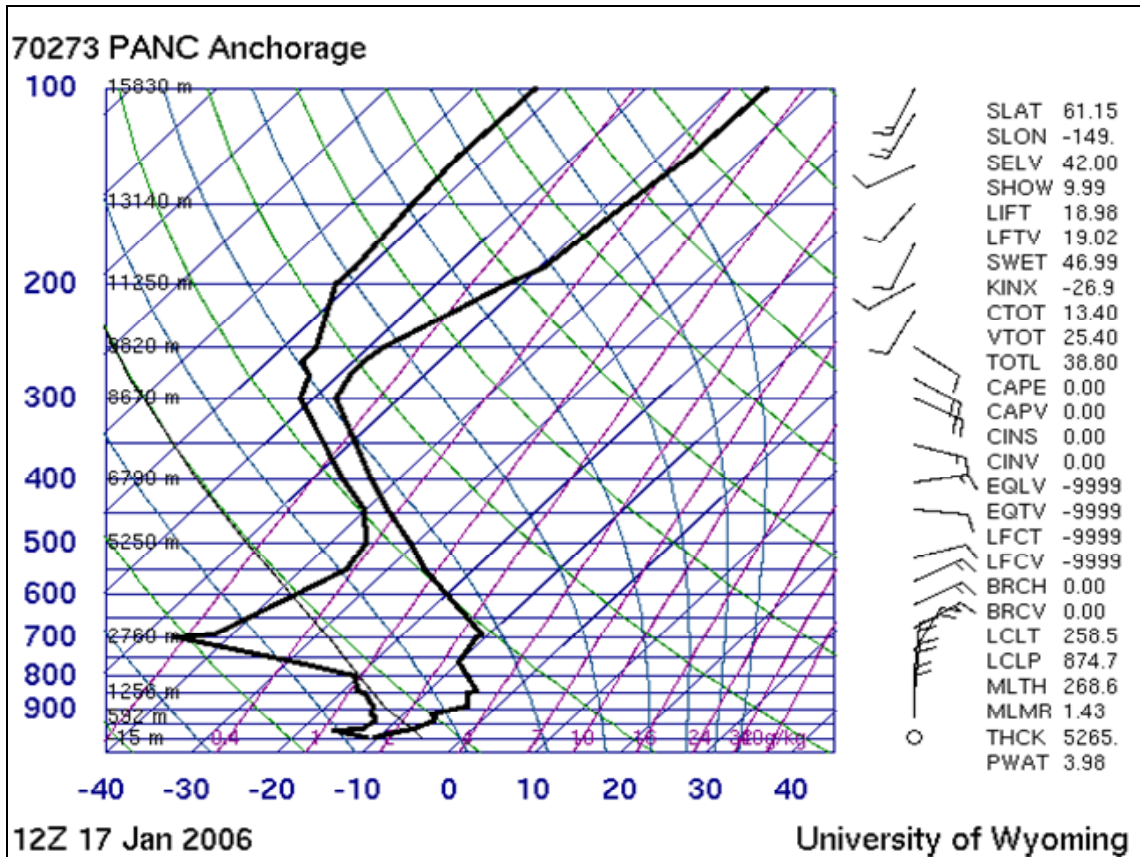


Figure 50. Upper-air sounding from PANC launched at 12Z 17 Jan 2006. From UWSP, 2007.

The 12Z sounding from 17 Jan (Fig. 50) showed a nearly saturated surface, but drying just above the surface. The observation from PANC at 12Z had temperature and dew point of -15°C/-16°C. So, it appeared as if fog formation would have been favorable. However, like the previous cases,

moisture increased just above the surface, and by the 00Z sounding on 18 Jan, the saturated layer stretched up some 400m from the surface. This is believed to again correlate with high tide, and moisture advection from the water source just above the surface.

70273 PANC Anchorage

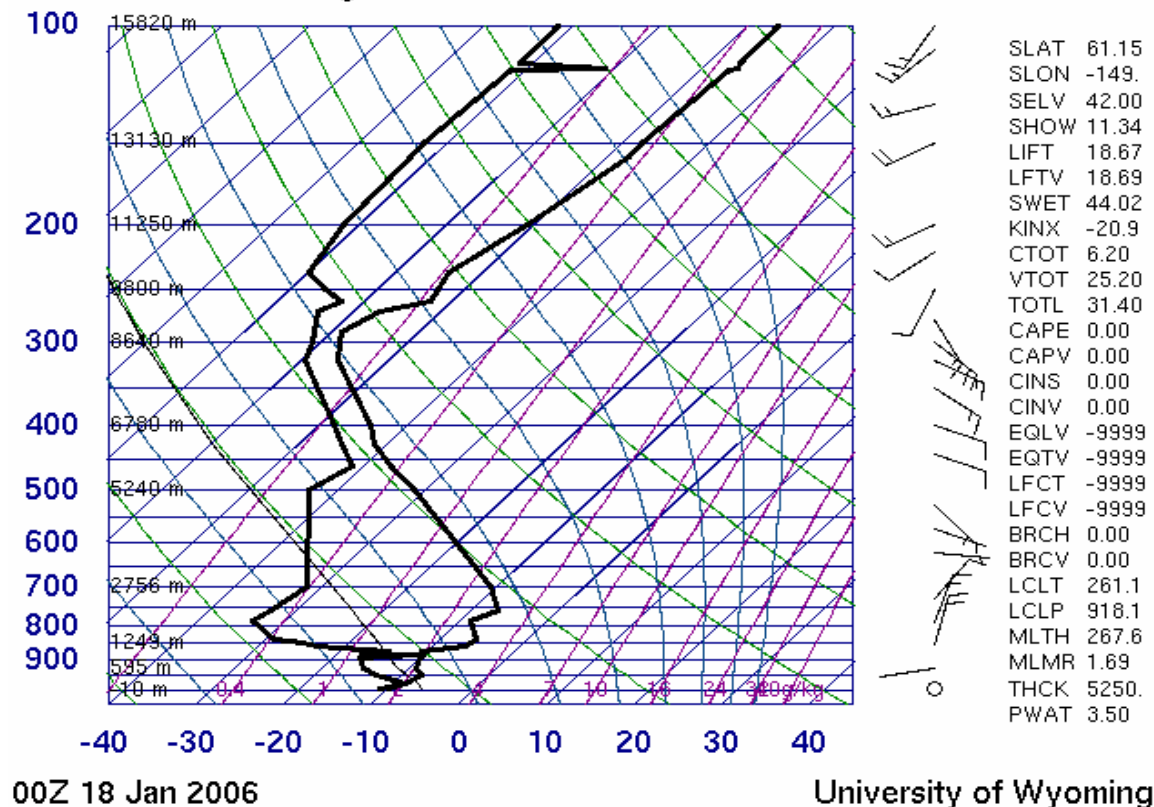


Figure 51. Upper-air sounding from PANC launched at 00Z 18 Jan 2006. From UWSP, 2007.

At 00Z on 18 Jan, the sounding from PANC indicated nearly saturated conditions at the surface, with a likely cloud deck at both 100 m based on the temperature and dew point temperature profile (Fig. 51). The staggered profile at 800 m was likely the result of sensor error. The big change from the previous sounding was the moisture increase that had occurred just above the surface. This had happened in the previous cases, and seems to be a forewarning of fog

formation. Since this was a 00Z sounding, it was taken during daylight, just before sunset. It is likely that radiational cooling after sunset would be enough to force saturation (or at least allow for fog to slide into the region).

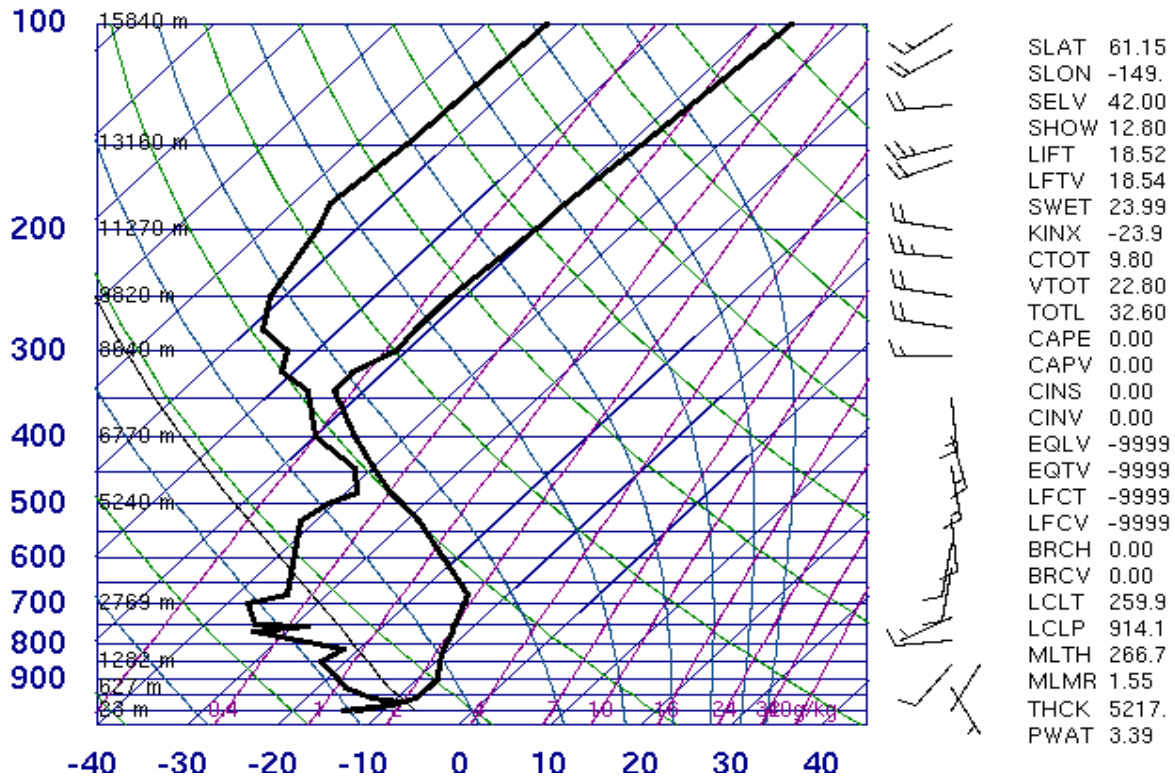


Figure 52. Upper-air sounding from PANC launched at 12Z 18 Jan 2006. From UWSP, 2007.

By 12Z on 18 Jan, the surface had cooled even further (Fig 52) to the point where the boundary layer appeared saturated. This depth of the saturated level was now as high as 400m, which is much greater than what would be expected from radiational fog alone. There was a strong inversion in place, and very dry conditions above 950mb, which would likely have been favorable to help sustain the fog through evaporational and radiational cooling (which assists in condensation at the top of the cloud layer), and would also help to compress the boundary layer. What impact this drying had on air parcel movement is only speculation, and no ice crystals were observed during this event.

4. Case Summary

This case started with a pressure gradient over the base aligned in an east-west fashion, and winds within the boundary layer were strong (>15kts) and from the northeast. As time went on, a low pressure center formed just east of the base, and changed the pressure gradient to make it more north-south. The winds subsided just above the surface, and a stratus deck formed. This stratus deck was observed for nearly 8 hours before fog formed, which lasted for approximately 11 hours. While this event was not as severe as the previous cases, the synoptic pattern, observations and soundings had very similar characteristics.

The conclusion about this event is that the fog formed up against the Chugach Mountains as a result of moisture advection (drainage flow). The fog pooled up against the mountains just after sunset, and it stayed there until enough radiational cooling took place at the base, which allowed the fog to drain into the region. When the fog drained into the area, this caused the wind to pick up to 4 kts, and be from an easterly direction. Daytime heating after sunrise on 18 Jan was presumably enough to mix out the fog over the base, although areas closer to the mountains did not receive enough sunlight to mix the boundary layer. The satellite images verified that the fog was off-station, but was still in the vicinity. Had the low pressure center not moved so close to the base, it is believed that fog would have occurred the next night. However, the low, and the associated positive vorticity advection, were enough to create snowfall on the next day, and raise the boundary layer through vertical ascent and surface convergence.

F. SUMMARY OF RESULTS

All four of the cases studied were very similar, with only subtle differences in the physical properties and dynamic characteristics of the boundary layer and atmosphere in general.

The synoptic pattern in all four cases (Fig. 53) resulted in a pressure gradient that forced winds from the north, which helped to advect cold air from the Alaskan Interior to the Anchorage Peninsula. This pattern almost always seemed to be the result of three things: 1) A low pressure center southeast of the base, that had an inverted trough extending over the base, 2) A high pressure center near the AK/CAN border, with an associated ridge into the Alaskan Interior, 3) Either a high to the west with a ridge stretching towards the Aleutian Chain, or a low to the west, with a trough extending towards the Aleutian Chain. If these criteria were met, the most favorable fog-producing pressure gradient existed. There were a few exceptions noted, however.

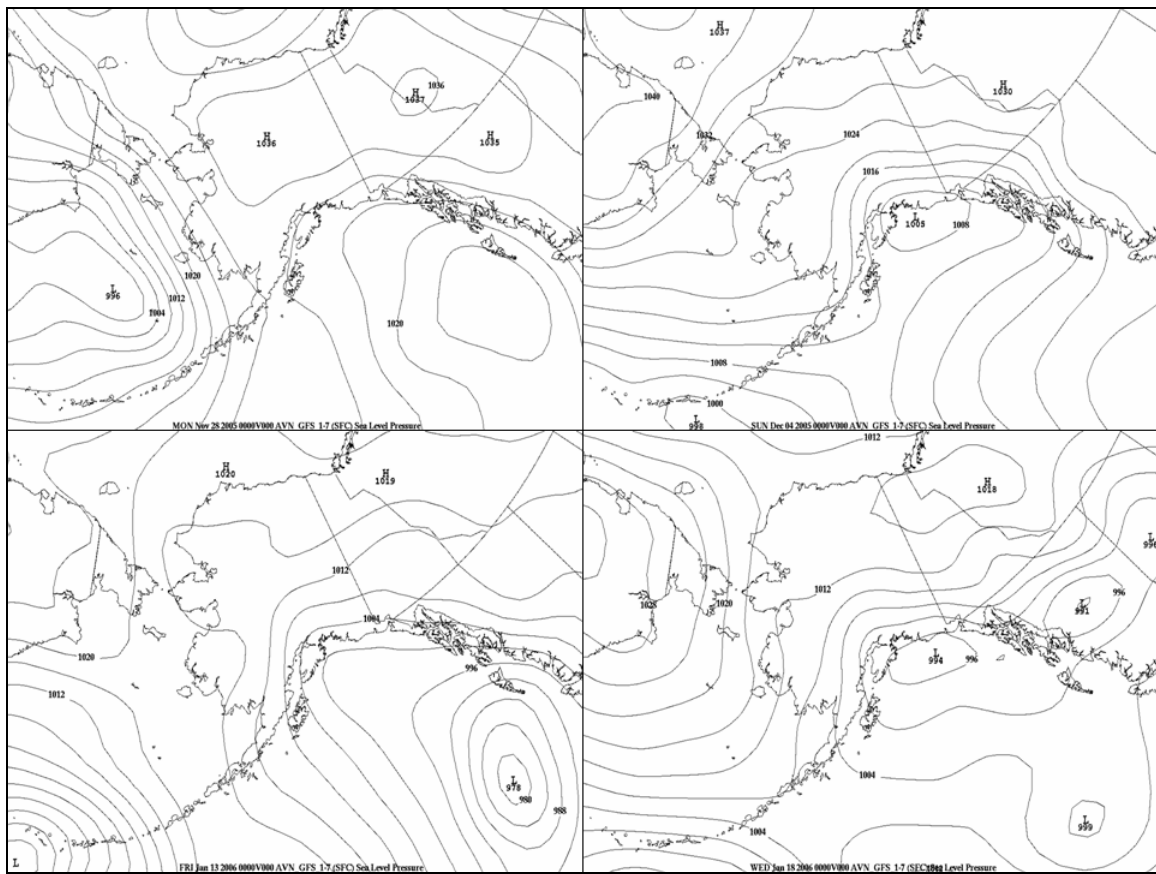


Figure 53. 4-pan sea-level pressure analyses for AK at 00Z on 28 Nov 05(top left), 04 Dec 05(top right), 13 Jan 06 (bottom left) and 18 Jan 06 (bottom right). From NCAR/NCEP, 2007

First, if this synoptic pressure gradient was too strong, winds would horizontally mix the boundary layer, demoting the formation of fog. Also, if it was aligned in any direction but north, the air mass did not appear to be cold enough to allow fog to form under normal diurnal conditions. And finally, if the low center moved too close to the base, vertical motion increased, presumably from surface convergence and positive vorticity advection, and the boundary layer rose (and was typically accompanied with light snow).

In addition to the similar synoptic pattern, all four cases shared a common thread, and that was a layer of stratus that was observed at PAED either just before, or at onset of fog formation. When compared to tidal data, the timing of the stratus correlated well with high water levels as recorded by NOAA. This correlation seemed to be very important from a forecast perspective, which will be discussed in Chapter V. The stratus appeared to form as a result of moisture flux into the layer from 150m-300m, as was evident from sounding data. This was likely the result of an increase in water surface area in an environment that was mainly ice and snow covered (and presumably dry), creating a moisture flux that produce ample moisture to be condensed as it entered the cold ambient air. The level at which it condensed appeared to be related to the temperature of the air mass in place. The colder the air mass, the closer to the ground the moisture could condense. In all cases, however, the stratus deck appeared to be no more than 200 ft above the ground at the base.

A final correlation was the wind direction at the surface at the time when fog was observed. When the fog was reported on station, the winds were often from a northeasterly-easterly direction. This would support the theory that the fog was actually forming on the northeast side of the base, and draining down when conditions were favorable. Satellite also verified that fog was common along the base of the Chugach Mountains to the east. Since the air mass appeared to be warmer and moister than that at the base, it could not have drained towards the base through thermal advection, since cold air would tend to advect towards warmer air. In order for the fog to get to the base, an advective

force had to be in play. This forcing is believed to have come from drainage winds in the valleys of the Chugach Range. These cold winds (trapped in a sunless valley between high ridges) were likely pouring out into the Anchorage Peninsula. Upon doing this, the cold air condensed the moisture from the high tides, and slowly pushed the newly formed warmer and moister fog towards the base. While this cannot be proven without more robust observations, it certainly provides an answer to how the fog forms, why it is always against the base of the mountains, and why the temperature and dew point temperature were increasing when the fog arrived.

Other results indicate the potential for vertical mixing of moisture to the surface, since the moisture flux and temperature changes fluctuated, which was not easily explained by the “sloshing” of the fog into the area. If the fog was coming and going, then the temperature and dew point temperature changes would make more sense. But when the temperature and dew point temperature changed without a change in the observed fog, this indicated that the moisture and heat source must be coming from the vertical and not the horizontal. Also, ice crystals in observations occurred, although not in all of the events. The ice crystals also appeared sometimes just before snow fall, so it is not possible to know if the sensor made an error in labeling very light snowfall as ice crystals. There were times when ice crystals were reported for hour-after-hour, and no snow was reported. It is theorized that in this case, the ice crystals were actually forming at the top of the stratus layer, and settling to the surface. A temperature of -18C or lower appeared to be favorable for this occurrence.

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V. SUMMARY AND CONCLUSIONS

A. SUMMARY

This study set out to determine the physical causes for the spontaneous and seemingly complex freezing fog formation at Elmendorf AFB, AK during the winter months. This was accomplished by compiling the model data, surface observations, satellite data, tidal data, and upper-air soundings for four known fog events, and studying each case for common threads that would link everything together. The results led to the conclusion that the fog in all of the cases was “draining” towards the base, and therefore will aptly be referred to as “Drainage Fog”.

Drainage fog was the name given to the fog that formed as a result of cold drainage winds from mountain valleys, interacting with a moist pool of air that advected to the base of the Chugach Mountains from Cook Inlet, and more specifically, Knik Arm. While the fog itself could not drain, because it was much warmer than the air at the base, it was gently “forced” by drainage winds out of the valleys. This explained not only the change in winds from the direction of the fog at onset, but also explained how a more warm and moist air mass could flow to a colder and more dry air mass.

The moisture is available twice per day (during the bimodal high tide), and condenses somewhere between the source region and the mountains, provided the winds are light. If the winds are too strong, too much horizontal mixing occurs, preventing condensation. This moisture saturates the boundary layer, and either condenses immediately upon entering the boundary layer (if the air mass in place is extremely cold), or rises to a level where it will condense (which from observations, appears to be between 150m-300m).

Cold air, from three major valleys to the east of the base, drains at all hours during the winter time, since the mountains are aligned latitudinally, which

prevents any solar radiation from reaching the north face of the mountains (except that little bit which may be reflected by clouds and the opposing face). These valleys drain out towards the Anchorage Peninsula, where it is able to interact with the somewhat warmer and moister air mass in place. It is not certain whether fog is already formed, or that the cold drainage flow is required to condense the moisture, but the net result is the same. The fog then moves towards the base through a natural thermal gradient and downslope between the base of the mountains and the base.



Figure 54. 3-D Depiction of Drainage Fog Formation. The moisture source to the north drifts south. Map courtesy of Google Earth, 2007.

B. FORECASTING DRAINAGE FOG

In order to more accurately forecast drainage fog, a few key parameters should be reviewed. It should be made clear that these recommendations will only lead to a “drainage fog” forecast, and will not provide the proper information to forecast radiation fog or advection fog, which also occur at the base.

First, a forecaster should begin by looking at the synoptic surface pressure pattern. In order for freezing fog to occur, a northerly wind component just above the surface needs to be in place, and can be recognized by the surface pressure analysis. This enables cold air to drain into the area from the north, and provides a vector for the moisture to flow towards the mountains and the base. Easterly winds may also be cold, but would carry moisture away from the base.

Once the pressure pattern is determined, tidal data should be reviewed, to gain knowledge into when high tide is forecasted to occur. If high tide is forecasted to occur, and winds just above the surface (between 1013-975mb) are from the north or northwest and light (less than 6 kts), moisture advection is likely to occur, which will pump moisture towards the base of the Chugach Mountains.

The surface winds should be reviewed next, to make sure they are extremely light, and northeasterly-easterly. While the winds may not actually blow until the fog is on station, any winds greater than 4 kts or from a direction other than 020-090 will be unfavorable for freezing fog formation.

Finally, forecast soundings should be consulted, to determine the amount of cooling expected in the lowest levels (lowest 100mb), and to see if a dry layer will develop at 850mb. While the forecast sounding may not depict the moisture flux just above the surface, the diurnal tendency for temperature gain and loss, as well as the overall temperature and moisture signatures within the boundary layer should be realized.

With all of these tools, a forecaster can now decide whether or not fog will form. If any one of the parameters above does not occur, it is believed that fog will not form (Fig. 55).

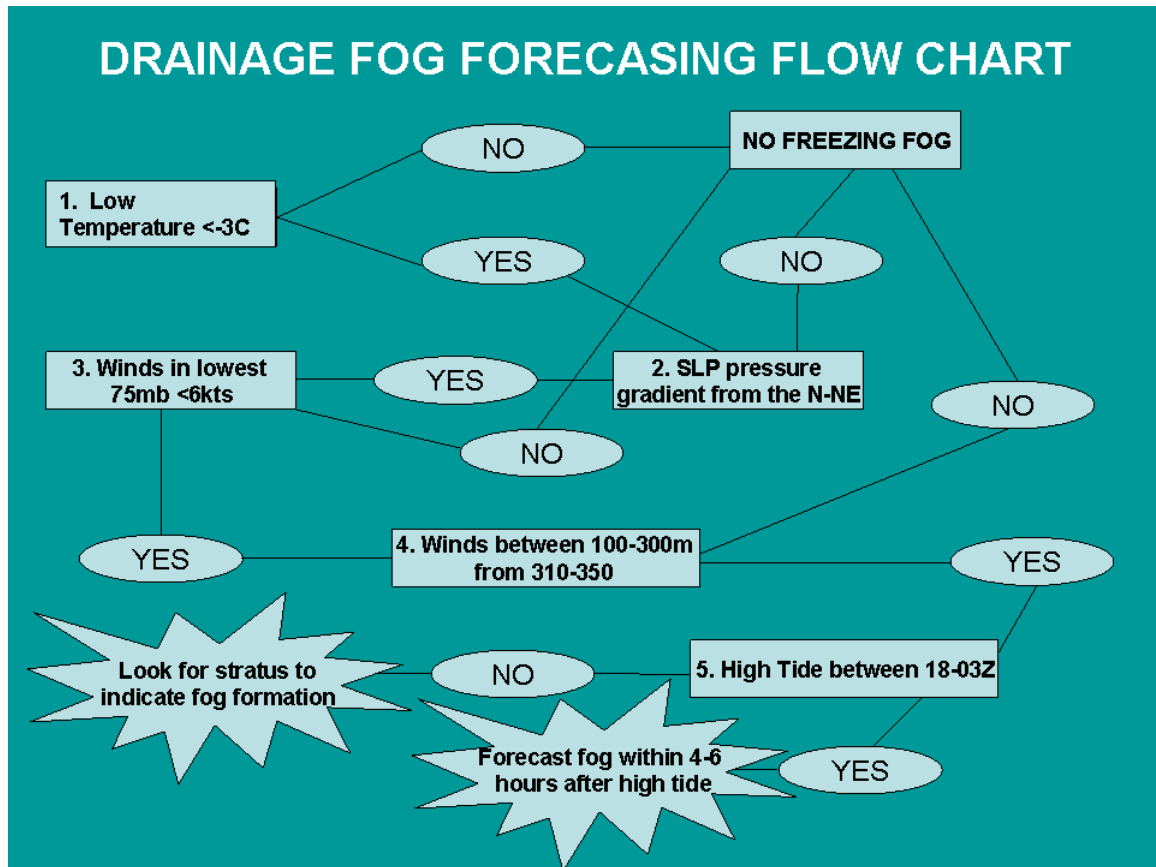


Figure 55. Drainage Fog Forecasting Flow Chart. This should be utilized by forecasters anytime the forecasted low temperature is expected to be below -3°C

C. RECOMMENDATIONS FOR FUTURE RESEARCH

While it would have been ideal to solve the entire fog forecasting challenge for Elmendorf AFB, this was obviously not feasible. There are a few things left to future research.

To begin with, more data stations would be useful to determine upstream observations. Having a few data points along the Knik Arm may provide more

information into the interaction of the tide and the boundary layer. In additions to stations along Knik Arm, a few stations at a heading of 050 at about 5 miles away from PAED would be very helpful. This appears to be a main region for the development of fog, and having these observations may be tell-tale to when the fog actually forms.

An increase in upper-air data would of course be useful as well. While sending up RAOB Balloons is costly, having a few floating balloons just above the surface (at 100 ft, 200 ft and 300 ft) would give a lot of information about the moisture content near the surface. These balloons (similar to what the Joint Inter-Agency Task Force-South uses in Key West, FL) could measure wind, temperature, dew point, and pressure, a can stay afloat constantly. They would be most telling if they were at a heading of 050 at about 5 miles away from PAED.

Finally, a more accurate radiation budget analysis of the area would be critical to determine what rate the surface needs to cool in order for the fog to drain into the region. Measurements at the base and near the base of the Chugach Range would provide a lot of information into the amount of cooling that happens prior to and during the fog events, and would also help to verify whether the drainage from the valley actually forms the fog or just sustains it.

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LIST OF REFERENCES

- Air Force Combat Climatology Center, cited 2007. [Accessed online at <http://www.afccc.af.mil>]. Accessed March 2007
- America's Roof, cited 2006. [Accessed online at <http://www.americasroof.com>]. Accessed March 2007
- Bowling, S.A., Ohtake, T., and Benson, C., 1968, Winter Pressure Systems and Ice Fog in Fairbanks, Alaska, *J. Meteor.*, **7**, 961-968.
- Center for Land Use Interpretation, The, cited 2007. [Accessed online at <http://ludb.clui.org>]. Accessed March 2007
- Center for Operational Oceanographic Products and Services, cited 2007. [Accessed online at <http://tidesandcurrents.noaa.gov>]. Accessed March 2007
- Climate Prediction Center (CPC), cited 2007. [Accessed online at <http://www.cpc.ncep.noaa.gov>]. Accessed March 2007
- Elmendorf Air Force Base (EAFB), cited 2007. [Accessed online at <http://www.elmendorf.af.mil>]. Accessed March 2007
- Fett, R.W., and Englebreton, R.E., 1993, Forecasters Handbook for the Bering Sea, Aleutian Islands, and Gulf of Alaska, *Naval Research Laboratory, Monterey*, 133 pp.
- Fitton, E., 1930, The Climates of Alaska. *Mon. Wea. Rev.* **58**, 85-103.
- Foreign Agricultural Services, cited 2007. [Accessed online at <http://www.fas.gov>]. Accessed March 2007
- Fukuta, N., 1968, Experimental Studies on the Growth of Small Ice Crystals, *J. Atmos. Sci.*, **26**, 522-531.
- Fukuta, N., and Gramada, C.M., 2003, Vapor Pressure Measurement of Supercooled Water, *J. Atmos. Sci.*, **60**, 1871-1875.
- Geology and Earth Science, cited 2007. [Accessed online at <http://geology.com>]. Accessed March 2007
- Girard, E., and Blanchet, J.-P., 2001, Microphysical Parameterization of Arctic Diamond Dust, Ice Fog, and Thin Stratus for Climate Models *J. Atmos. Sci.*, **58**, 1181-1198.

GlobalAir.com, cited 2007. [Accessed online at <http://www.globalair.com>]. Accessed March 2007

Google Earth, cited 2007. [Accessed online at <http://www.googleearth.com>]. Accessed March 2007

Gotaas, Y., and Benson, C., 1965, The Effect of Suspended Ice Crystals on Radiative Cooling, *J. Meteor.*, **4**, 446-453.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-year reanalysis project. *Bull. Amer. Meteor. Soc.*, **77**, 437-471.

Kyle, R., and Brabets, T., 2001, Water Temperature of Streams in the Cook Inlet Basin, Alaska, and Implications of Climate Change, *USGS Water-Resources Investigations Report*, 24 pp.

Li, C., Li, X., and Pichel, W.G., 2004, Tidal Convergence Fronts in Cook Inlet, Alaska, *American Geophysical Union*, 22 pp.

Makkonen, L., and Laasko, T., 2005, Humidity Measurements In Cold and Humid Environments, *Boundary-Layer Meteorology*, **116**, 131-147.

Meteorological Assimilation Data Ingest System (MADIS), cited 2007. [Accessed online at <http://madis.noaa.gov>]. Accessed March 2007

MODIS Rapid Response System, cited 2007. [Accessed online at <http://rapidfire.sci.gsfc.nasa.gov>]. Accessed March 2007

National Centers for Environmental Predictions (NCEP), cited 2007. [Accessed online at <http://www.ncep.noaa.gov>]. Accessed March 2007

Plymouth State Weather Center, cited 2007. [Accessed online at <http://vortex.plymouth.edu>]. Accessed March 2007

Schnell, R.C., 1977, Ice Nuclei in Seawater, Fog Water, and Marine Air of the Coast of Nova Scotia: *Summer 1975*, *J. Atmos. Sci.*, **34**, 1299-1305

Song, N., and Lamb, D., 1993, Experimental Investigations of Ice in Supercooled Clouds. Part I: *System Description and Growth of Ice by Vapor Deposition*, *J. Atmos. Sci.*, **51**, 91-103.

University of Waterloo, cited 2007. [Accessed online at <http://www.science.uwaterloo.ca>]. Accessed March 2007

University of Wisconsin, Stevens Point, cited 2007. [Accessed at <http://www.uwsp.edu>]. Accessed March 2007

University of Wyoming, Department of Atmospheric Sciences, cited 2007. [Accessed online at <http://www.weather.uwyo.edu>]. Accessed March 2007

Virtual Tourist, cited 2007. [Accessed at <http://www.virtualtourist.com>]. Accessed March 2007

Weather Underground, The, cited 2007. [Accessed at <http://www.wunderground.com>]. Accessed March 2007

Wendler, Gerd, 1968, Heat Balance Studies During an Ice=Fog Period in Fairbanks, Alaska, *Mon. Wea. Rev.*, **97**, 512-520.

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